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PLASMA WAVE EXPERIMENT  
FOR THE ISEE-3 MISSION

by

F. L. Scarf,  
Principal Investigator

(NASA-CR-170556) PLASMA WAVE EXPERIMENT FOR N83-13750  
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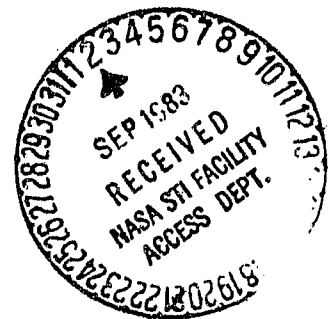
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16. Abstract  <p>The objective of this contract is to provide analysis of data from a scientific instrument designed to study solar wind and plasma wave phenomena on the ISEE-3 Mission. (The hardware phase of the contract was completed in 1978, and the final report for that phase has been submitted. The data analysis phase is on-going and is the portion of the contract that continues to be reported on.)</p> <p>This report is the Fifth Semi-Annual Report, submitted in compliance with Modification 19 to Article XXI of Contract NAS5-20682, entitled, "Plasma Wave Experiment for ISEE-C (Heliocentric) Mission," dated 20 November 1974.</p> <p>The purpose of this report is to summarize the performance of work on the data analysis phase of the contract during the period commencing 20 February 1982 and ending 19 August 1982.</p>					
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## PREFACE

### 1. OBJECTIVE

The purpose of this report is to summarize the performance of work for the period 20 February 1982 through 19 August 1982, in compliance with Modification 19 to Article XXI of Contract NAS5-20682, entitled, "Plasma Wave Experiment for ISEE-C (Heliocentric) Mission," dated 20 November 1974.

The objective of this contract is to provide analysis of data from a scientific instrument designed to study solar wind and plasma wave phenomena on the ISEE-3 Mission.

### 2. SCOPE OF WORK

Project activities during this past six months have included successful return of data from the instrument, continuing analysis of all data, publication of results, and deposit in National Space Science Data Center of the data.

### 3. CONCLUSIONS

Not applicable.

### 4. SUMMARY OF RECOMMENDATIONS

Not applicable.

## 1.0 INTRODUCTION

The purpose of this report is to summarize the various activities and tasks accomplished on the data analysis phase of the contract during the 29th and 30th quarters of work.

## 2.0 WORK ACTIVITIES FOR THE SIX-MONTH PERIOD

### 2.1 Research

During this interval, there was much research activity involving the ISEE-3 Plasma Wave Investigation and the (unfunded) counterparts on ISEE-1 and -2. The paper, "Plasma Wave Levels and IMF Orientations Preceding Observations of Interplanetary Shocks by ISEE-3," by Greenstadt et al., appeared in Geophys. Res. Lett., 9, 668, June 1982; and the paper, "Whistler Mode Turbulence in the Disturbed Solar Wind," by Coroniti et al., appeared in J. Geophys. Res., 87, 6029, August 1982.

Three additional papers were completed. "Large-Amplitude Magnetic Variations in Quasi-Parallel Shocks: Correlation Lengths Measured by ISEE 1 and 2," by Greenstadt et al., has already appeared in Geophys. Res. Lett., 9, 781, July 1982 (Appendix I). "Computer-Constructed Imagery of Distant Plasma Interaction Boundaries," by Greenstadt et al., was prepared for the Workshop on Advances in Instrumentation and Data Display Related to Space Plasmas of the 24th Plenary Meeting of COSPAR, held in Ottawa, Canada, May-June 1982 (Appendix II). Gene Greenstadt cooperated with Chris Russell in preparing a review paper, "Magnetospheric Boundaries," as a contribution to the 1983 U.S. National Report to IUGG, and this paper has been submitted for publication in Reviews of Geophysics and Space Physics (Appendix III).

## 2.2 Other Activities

During the six-month period, F. L. Scarf made many trips to Washington to discuss alternate plans for ISEE-3. In March, he presented the arguments for sending ISEE-3 to the Tail at a NASA Headquarters conference. He also participated at that time in a discussion of the benefits associated with an ISEE-3 mission to Comet Giacobini-Zinner. In June, Dr. Scarf participated in a second meeting at NASA Headquarters on the same topic, and on the next day, he participated in an ISEE-3 presentation to the Space Science Board of the National Academy of Sciences.

In addition, Dr. Scarf spoke about ISEE-3 measurements at the libration point and future prospects from the Earth's Tail and from the Comet Encounter when he visited the Soviet Union as the guest of the Space Research Institute, Moscow, in April.

During this period, C. F. Kennel gave a talk on ISEE-3 data at the American Geophysical Union meeting held in Philadelphia in May, and he presented seminars on ISEE-3 results at Los Alamos National Lab in April, and at the Institute for Theoretical Physics, Santa Barbara, in June.

LARGE-AMPLITUDE MAGNETIC VARIATIONS IN QUASI-PARALLEL SHOCKS:  
CORRELATION LENGTHS MEASURED BY ISEE 1 AND 2

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**Abstract.** Wide separations up to more than 1  $R_E$  between ISEE 1 and 2 during the second half of 1978 have been used to measure the correlation length of magnetic pulsations in quasi-parallel shocks. When the two spacecraft were less than a few hundred km apart, magnetic oscillations measured by magnetometers on both spacecraft exhibited virtually identical waveforms, but at distances of several thousand km, the two time series of field variation showed no detailed similarity at all. The correlation coefficients of the pulsations dropped from close to 1.0 for spacecraft separations of less than 100 km to 0.2 for separations of greater than 800 km. A correlation length of several hundred km may be related to the gyroradius of return protons with energy typical of the peaks of diffuse and beam ion distributions.

#### Introduction

Simultaneous measurements by two or more instruments at different locations within the Earth's bow shock and foreshock regions constitute the essential tool for distinguishing temporally from spatially varying structures. So far, analysis of data from the satellite pair ISEE 1 and 2 has emphasized the mutual consistency of their measurements. Indeed, one of the striking features of the earliest data from the magnetometers of ISEE 1 and 2 was the detailed similarity, under normal conditions, of waveforms at the two vehicles even in the highly-irregular, large-amplitude perturbations of the quasi-parallel shock, of which examples are shown in this report. A high  $\beta$ , of course, even the quasi-perpendicular profile differs from one spacecraft to the other [Russell and Greenstadt, 1979]. Signal correlation, because of its obvious application to timing the motions of waves and boundaries between the satellites, has therefore received much attention, and, in fact, one study has successfully defined propagation vectors and velocities of ULF waves in the foreshock [Hoppe and Russell, 1980; Hoppe *et al.*, 1981]. The limits of correlation are equally of interest, however.

In contrast to most of the early data from

the ISEE project, which were obtained when the satellites were close together (i.e., within a few hundred km of each other), the data from the second half of 1978 offer the first opportunity to examine directly the extent of signal correlation, hence spatial variation, in the local plasma environment when the two spacecraft passed through bow shock distances at varying separations up to several thousand km. This report presents the first documented change of correlation with distance for a magnetic constituent of the shock structure and discusses a possible relationship of correlation length to ion gyroradius. Our examples are all quasi-parallel, by which we mean the angle between the interplanetary magnetic field and the local model shock normal was less than about 50° and large-amplitude field oscillations were recorded.

#### Variable Correlation

Figure 1 offers a visual display of the variations in wave correlation observable in the running 12-second averages (plotted every four seconds) between ISEE 1 and ISEE 2. In 1(a), the two traces of magnetic-field magnitude exhibit almost identical waveforms. Moreover, the similarities of changing field pattern occurred in both the ULF foreshock waves (e.g., around 0015 and 0030) and in the larger-amplitude waves and pulses defining the outer edges of the quasi-parallel shock structure, as seen between 0020 and 0024. The fidelity of wave duplication at the two spacecraft persists at higher resolution, illustrated in Figure 2, where we see unaveraged data with samples recorded every 0.25 second. A segment of the data from Figure 1(a) is shown in Figure 2(a). While not identical in every detail, or exactly alike in amplitude, the two waveforms shared essentially the same pattern for periods of a few seconds or longer, and the occurrence of higher-frequency bursts was almost simultaneous at both satellites in the illustrated examples. Figure 2(b) is an overlay of ISEE 1 and ISEE 2 data for a section of 2(a), showing clearly the close similarity of the two signals, albeit with slightly variable delay from one satellite to the other.

Returning to Figure 1, we note that in 1(b) the similarity of the two field plots is considerably less pronounced than in 1(a). Indeed,

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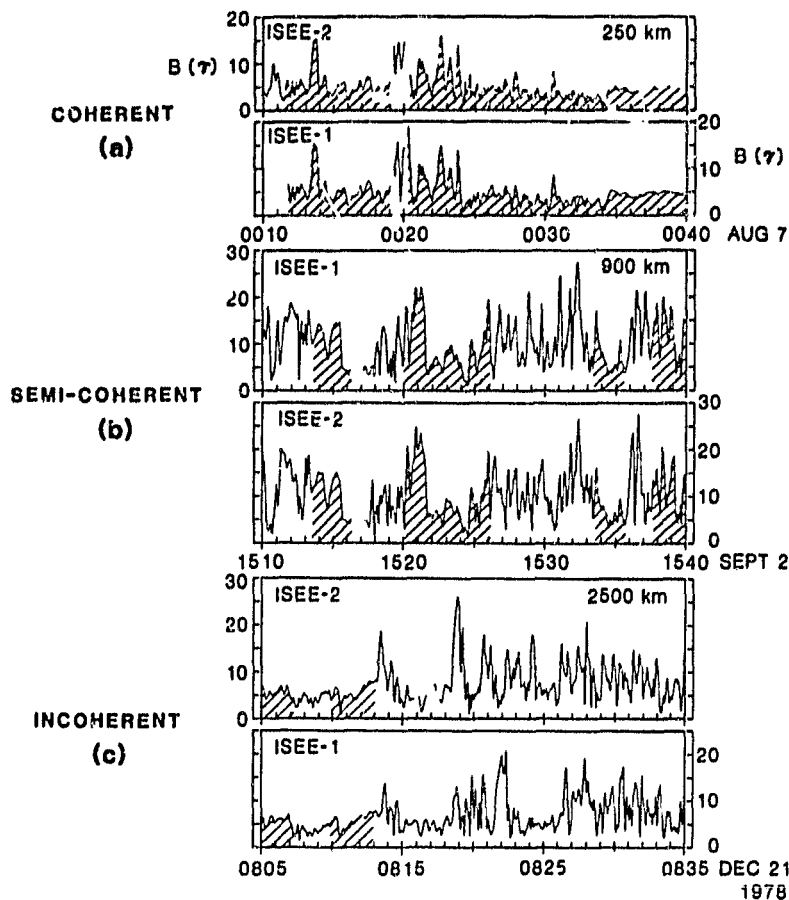


Fig. 1. Three cases showing the decrease in coherence with increasing separation between ISEE 1 and 2. Shading indicates intervals of similar waveform.

there are only limited sections, shaded for emphasis, where we would assert the credibility of such a correlation on the strength of pattern inspection alone. In Figure 1(c), an interval is shown in which there appears to have been still less correlation between the waveforms at the two spacecraft than in case 1(b). In particular, while sections of similar patterns persisted among the smaller, foreshock waves (shading), the larger-amplitude pulsations have visibly lost any sign of correspondence outside of their simple joint occurrence. Certainly, the contrast between 1(c) and the pervasive waveform reproduction of 1(a) is clear. Overall, then, Figure 1 illustrates the range of variability of waveform correlation recorded in the quasi-parallel shock and foreshock.

#### Decrease of Correlation With Distance

In each of the pairs of panels of Figure 1, at the upper right, is printed the distance, 250, 900, or 2300 km between ISEE 1 and ISEE 2. Clearly, the separation in 1(c) was ten times that in 1(a). This implication has been made more quantitative by computing cross-correlation coefficients for 20 pairs of such cases in which the upstream  $\beta$  ranged from 0.7 to 3.0, the solar wind Mach number from 5.0 to 6.5, and the local normal angle from  $10^\circ$  to  $\geq 45^\circ$ .

Correlation coefficients averaged over four-

minute intervals were calculated for successive 0.25-sec lags, consistent with the magnetometer's acquisition rate of four vectors per second. The correlation coefficient present in this report is that of the average lagged product of the time series on the two spacecraft for each of the three vector components weighted by the variance in that component. Further details can be found in the paper by Hoppe and Russell [1980].

Figure 3 is a plot of the cross-correlation coefficients of large-amplitude, quasi-parallel shock pulsations for the 20 cases, at spacecraft-separation distances ranging from 105 to 5,700 km. The graph demonstrates the fall-off of pulse correlation with distance, showing nearly perfect correlation at the left and nearly complete lack of correlation at the right. We have not regarded the preliminary data of Figure 3 as sufficiently refined to justify fitting the points with an exponential or other heuristic model; we infer, tentatively, that the correlation remains high, but declines progressively with separation up to several hundred km, then drops rapidly to essentially no correlation at a threshold distance of about 1,000 km. One argument against reading the length scale too carefully at this stage is the unknown role that gross motion of the whole shock may have played in the data set. We may hope that any such effect would have averaged



out over many examples where the shock moved both in and out. A reliable assessment of shock motion by two satellites inside the quasi-parallel structure, a prerequisite configuration for a correlation study, is naturally precluded. The figure suggests, then, that the outermost part of the quasi-parallel shock pulsations occur in fairly well-marked "cells" containing magnetic fluctuations of common origin, distinguishable from fluctuations in adjacent cells. We can call the cell dimension of about 1,000 km the "correlation length" of the pulsations.

We may imagine that a progressive decline of correlation occurs when a major wave component is damped with distance, so that its contribution is large at one spacecraft but inconspicuous at the other. While dissipation of wave energy with distance may take place, there is little indication that this effect is responsible for much of the observed variation in correlation. Corresponding sections of data at intermediate distances, as in Figure 1(b), for example, show no consistent amplitude difference from one observation point to another, and some of the correlation that does persist at longer distances, as in Figure 1(c), occurs in the smaller waves, which appear to retain their amplitudes very well [in the example of Figure 1(c), ISEE 1 was almost directly downstream from ISEE 2]. Thus, simple wave damping appears inadequate as an explanation for loss of correlation, especially the major loss at the edge of a "cell", and we need an alternative explanation.

#### Possible Relation To Return Particle Populations

We may also imagine that the bulk of an observed pulse train is produced by currents from an identifiable sub-population of particles such as return ions -- i.e., reflected or back-streaming ions [Gosling et al., 1978; Eastman et al., 1981; Sentman et al., 1981; Bonifazi and Moreno, 1981] -- in a region occupied by those particles. When both magnetometers are in the same region, they record the same wavetrain; when they are not, each records a wavetrain dominated by local currents but superposed on components propagated and/or convected from other regions upstream.

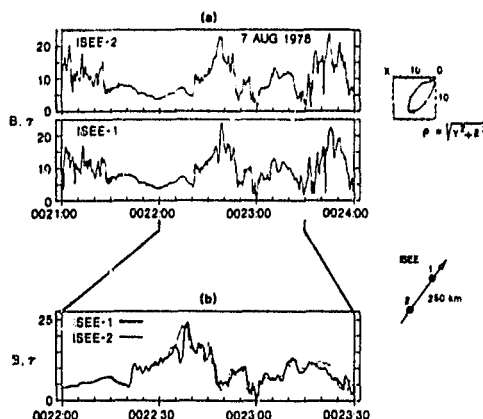


Fig. 2. Details of well-correlated pulsations shown in Figure 1(a). Inserts illustrate position of satellites and orientation of separation vector.

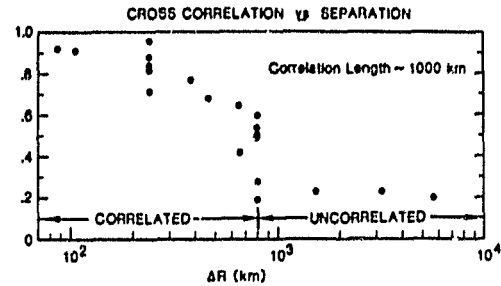


Fig. 3. Cross-correlation vs separation distance  $\Delta R$ .

According to this alternative explanation, the "correlation length" should be related to some characteristic particle-current dimension peculiar to the shock or foreshock, and this seems to be the case. In Figure 4, we reproduce the distributions of bulk and thermal velocities for the recognized categories of return (back-streaming) ions, which we know are present just outside the shock, as plotted by Bonifazi and Moreno [1981]. Treating these distributions as if they were representative of velocities perpendicular to the ambient field, we have added scales of equivalent Larmor radii at the bottom, using an average IMF of 5Y. We see at once that, regardless of category, virtually all the measured velocities would correspond to gyro-radii below about 2000 km. Moreover, the peaks of the distributions of diffuse-ion bulk velocity (at left) and reflected-ion thermal velocity (at right) occur at a few hundred km, where correlation is high in Figure 3. It is not unreasonable, then, that wave shapes are shared in regions occupied by associated return ions circulating around the local ambient field. The gyrophase-bunched ions described by Eastman et al. [1981] and Gurgiolo et al. [1981] come readily to mind.

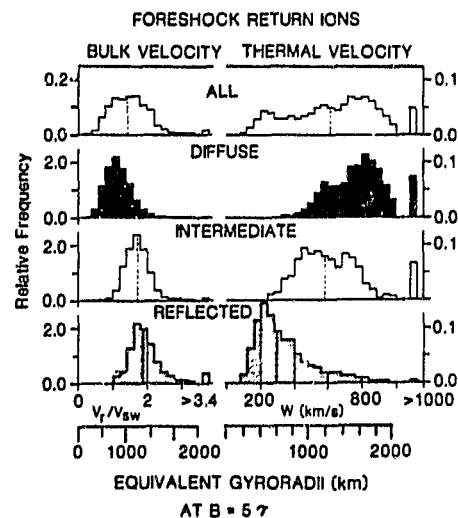


Fig. 4. Equivalent gyroradii of return ions studied by Bonifazi and Moreno (1981). In the original graphs, just above the gyroradii scales, symbols  $V_r/V_{sw}$  and  $W$  denote the ratio of return ion velocity to solar wind velocity (left) and return ion thermal speed (right).

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We have displayed our quantitative analysis for a few cases of the larger "pulsations" of the quasi-parallel shock under typical plasma conditions ( $\beta \approx 1$ ,  $M \approx 5$ ) and plotted the results against the straight-line distances separating the two spacecraft. The visual evidence in Figure 1(c), supported by additional cases not shown here, suggests that the smaller, foreshock waves retain their patterns better at large separation than do the pulsations. Clearly, a quantitative result pertaining to foreshock waves will be more difficult to achieve, since the total separation of the two satellites in the foreshock did not exceed about 7,000 km, which could be commensurate with, if not shorter than, the smaller waves' correlation length. Moreover, the correlation length may depend not on simple separation distance, but on distance along the ambient field, along the guiding center backstreaming direction, along the wave propagation vector, or along or across the solar wind flow. We have plotted correlation vs separation projected on the local shock normal and found a decline similar to that in Figure 3. We have also found that in all cases examined so far, the lag has always been from the spacecraft ahead in the solar wind to the one downwind. Numerous cases will have to be found, and extensive analysis done, to distinguish these possibilities reliably and to verify and understand the downwind delay in relation to particle behavior. We note, however, that a correlation length shorter for the large pulsations than for the upstream waves is compatible with the Larmor radii association mentioned above, as follows:

Recall that the distance scales at the bottom of Figure 4 were derived using an IMF magnitude of 5Y, since this is the average where the upstream distributions are found; but where quasi-parallel pulsations occur, the average field is often double the average nearby IMF. If the radius scales of Figure 4 were redrawn using a field of 10Y, the ion distributions would be concentrated at distances half those shown, implying very strong current and wave correlation at short separations, as documented in this report. Thus, small correlation lengths for the large waves and larger correlation lengths for the small waves argue for wave creation by identifiable groups, or beams, of return ions in regions measured by the appropriate gyroradii. Of course, the very long, actual correlation lengths of waves in the foreshock probably include the influence of convection by the fast, unshocked solar wind.

Foreshock ions already released from the shock and returned to the solar wind cannot fully represent the ions responsible for the correlation cells discovered here. While ions composing the foreshock return particles are doubtless also present in the outer edge of the quasi-parallel structure [Asbridge et al., 1978], an important measurement still to be

reported is the spectrum of trapped, or "second distribution", ions in the quasi-parallel pulsation structure itself. These should replace the spectra used in Figure 4. From such a spectrum, a more pertinent range of gyroradii can be inferred. We may then ask whether the quasi-parallel shock contributes its own identifiable seed distribution to the ions of the foreshock or whether the missing distributions are simply foreshock particles blown downstream. It is unclear at present how energetic ions derived entirely from upstream scatter of reflected ion beams [Bame et al., 1980] would retain or recover a sharply defined cell dimension on reentering the shock, but the alternative postulate that dispersed ion distributions are produced primarily by direct sources at or near the bow shock [Eastman et al., 1981] awaits systematic verification. Hopefully, detailed investigation of the ions themselves will contribute complementary information to the study of wave-particle interactions in the shock and foreshock, facilitated by the wide separations of the ISEE 1 and 2 spacecraft in 1978.

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COMPUTER CONSTRUCTED IMAGERY OF  
DISTANT PLASMA INTERACTION BOUNDARIES

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COMPUTER CONSTRUCTED IMAGERY OF  
DISTANT PLASMA INTERACTION BOUNDARIES

ABSTRACT

Computer constructed sketches of plasma boundaries arising in the interaction between the solar wind and the magnetosphere can serve as both didactic and research tools. In particular, the structure of the Earth's bow shock can be represented as a nonuniform surface according to the instantaneous orientation of the IMF, and temporal changes in structural distribution can be modeled as a sequence of sketches based on observed sequences of spacecraft-based measurements. Viewed rapidly, such a sequence of sketches can be the basis for representation of plasma processes by computer animation.

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## INTRODUCTION

Space scientists, concerned with the question "How are remote measurements of invisible physical variables to be transformed to easily interpretable representations of environmental plasma processes", have been turning to increasingly elaborate diagrams to portray their results. Figure 1, from the 1981 report of the Committee on Solar-Terrestrial Research [1], is a three-dimensional, static representation of the magnetospheric system, one of many such figures published in recent years. The picture satisfied a need for a visual way of exploring the relationships and relevance of various elements of the magnetosphere to each other in real, three-dimensional space, in part to persuade nonspecialists of the importance of a comprehensive program to study the earth's natural environment. Implicit in creation of such a figure, however, is the severe test to which its designers' knowledge of the magnetosphere is subjected. Since no one has ever seen most of the components of the figure, let alone the magnetosphere as a whole, the form in the picture is the result of numerous inferences from measurements of small parts of the whole; some of the inferences are controversial, qualitative, and interpolated or extrapolated from an incomplete library of observations. The designer learns a lot in preparing such a diagram with care.

Presumably drawings would become increasingly "correct" as the quantitative relations of one component to another became more precise with added measurements and refined theory, allowing also for temporal changes within the continuously varying environment brought by the solar wind. Quantitative expression of the information contained in Figure 1 must obviously involve the use of automatic computation on a large scale. It is not hard to imagine that if some parts of the magnetospheric system can be modeled, diagrams

like that shown can be made by computer, and the validity of models can be tested: Observed responses to observed solar wind changes can be visualized and compared with theoretically predicted responses. Thus computer-generated sketches could be a valuable research tool.

Figure 2 shows two components of the Earth's magnetosphere, namely the magnetopause surrounded by the bow shock. The magnetosphere is modeled as an ellipse according to the expression and parameters given by Holzer and Slavin [2, eq.(1)]:  $R = 1/(1 + \epsilon \cos \theta)$  where  $l = 15.0$ ,  $\epsilon = .4$ ,  $R$  is the distance in earth radii ( $R_E$ ) from the earth center, at one focus of the ellipse, and  $\theta$  is the angle between  $R$  and the sun-earth line. The magnetosphere is scaled to place its subsolar distance at  $C/(NV^2)^{1/6}$  according to ambient solar wind density  $N$  and speed  $V$ , with  $C = 6.46 \times 10^{10}$ . The bow shock is modeled as a symmetrized hyperboloid of revolution scaled to the ambient-determined subsolar point, as described by Greenstadt et al [3, eq. (2,3)]. The program that draws these sketches presents them from any selected viewpoint in spherical coordinates. A surface is outlined by its curves of intersection with the X-Y and X-Z planes, and the program can also insert the curve of intersection with a plane of arbitrary orientation. In addition, the program can insert a known observation point, i.e., a satellite position, trace a field line through the observation points to the shock, and draw lines through the observation point from the shock representing the trajectories of reflected particles, taking into account their  $E \times B$  drift velocities. The program also computes the angles between the local shock normals and any of the above lines at their point of intersection with the shock. With these kinds of computer-generated sketches, we have begun to explore the representation of plasma interaction phenomena. Our initial efforts have concentrated on the interplanetary

magnetic field B (the IMF) and its relationship to interplanetary shocks and to the earth's bow shock. The remainder of this report deals only with the bow shock.

#### SHOCK STRUCTURE.

The insert of Figure 3 is an illustration, essentially a cartoon, of a slice of the Earth's shock system in a plane containing the solar wind flow velocity (the X-axis) and the IMF, with the latter at an angle of  $45^\circ$  to the X-axis. The system consists of the nonuniform, hyperboloidal shock boundary, which is quasi-perpendicular (Q-perp) and essentially wave-free in the lowest section of its curve, and quasi-parallel (Q-par) and wave-dominated in the upper section of its curve. Inside (i.e., downstream from) the shock, the magnetosheath is also nonuniform, being quiet or turbulent according to the character of field distributed by the post shock convection pattern of the solar wind [4]. Outside (i.e., upstream from) the shock, the foreshock extends over a large volume of space whose shape and character are determined largely by the reflection and wave particle interactions of solar wind electrons and ions escaping the shock along the IMF in the frame of the flowing plasma. The graph below the insertion shows a typical magnetic field profile as observed by a spacecraft passing from the foreshock through the quasi-parallel shock into the magnetosheath. A quasi-perpendicular profile would consist, at the illustrated resolution, of little more than a quiet field plot jumping to a higher level at the shock, with some high frequency turbulence superposed [5].

Figure 3 serves to demonstrate that a realistic and useful representation of the shock system must display not only gross motions but some measure of the nonuniform structure as well. In addition, a good representation must show



the whole system in three dimensions, not just a plane, and must account for structural variations caused by the continuously changing IMF direction.

#### STATIC DIAGRAMS.

We have begun by attempting to depict the structure of the bow shock itself very simply, leaving the foreshock and the rest of the shock system for later development. For a given IMF orientation, the shock can be divided to first approximation into Q-perp and Q-par sections according to the angle between  $\vec{B}$  and the local shock normal. We have a choice of using the angle between  $\vec{B}$  and the normal to the shock ( $\theta_{Bn}$ ) or between  $\vec{B}$  and the normal to the curve of intersection of the shock in the B-X plane ( $\theta_{Bnc}$ ). We have used  $\theta_{Bnc}$  in preparing this report. Observations have found the division between Q-perp and Q-par structures to occur where the normal angle is between  $40^\circ$  and  $50^\circ$ . For the present we choose  $\theta_{Bnc} = 45^\circ$ .

Figure 4 displays the bow shock for two different orientations of the IMF. The shock surface is indicated by its curves of intersection with parallel B-X planes  $2.5 R_E$  apart; the Q-perp portion of each curve for which  $\theta_{Bnc} > 45^\circ$  is drawn with a solid line; the Q-par portion, for which  $\theta_{Bnc} < 45^\circ$  is drawn as a series of spaced tildens "~", representing the wave character of the Q-par structure. In the upper panel, the Q-perp part of the shock is on the morning (left) side; we illustrate such a case, which mirrors the typical, or average one, to emphasize the variable nature of the IMF. In the lower panel, a rotation of the IMF has rotated the B-X planes, hence the way in which Q-perp/Q-par structures would be distributed in the shock. Note at this point that all computer sketches are made after correction for solar wind aberration, so that the X-axis is the direction from which the solar wind flows. We shall refer to our frame as Solar Wind Coordinates (SWC).

Each of the sketches of Figure 4 are static depictions of the bow shock which would apply for a hypothetical  $B_{nc} = 45^\circ$  division, under circumstances in which the solar wind and the IMF remained constant for at least the time necessary to stabilize the shock structure from the subsolar point to our arbitrary termination of the sketch at  $X = -10$ . In reality, of course, the IMF is constantly varying, if only slightly, so no still picture is valid for long, and the shock is constantly in process of rearranging its structural nonuniformities. The logical way to "look at" the shock, therefore, is in a continuous sequence of sketches, so we have been preparing a short motion picture in which we try to animate the bow shock's behavior.

#### ANIMATION.

Our experiment with motion picture animation is essentially a pilot project to test the symbolic representation of shock structure. Ultimately, we look to real time computer animation, displayed on a CRT, as a research tool. For studying display methods and the animation concept in general, however, we have been combining data, equipment, and programs on hand. We read a stream of averaged IMF and solar wind data from disc into a Hewlett-Packard 9845B, whose attached multicolor X-Y plotter constructs a diagram similar to either of those in Figure 4 for each data sample, but with a sampling-rate effect described in the next paragraph. Our source of measurements is the ISEE-3 data pool tape, on which various parameters are stored at different averaging intervals. The shortest averaging interval for the parameters our program uses is that of the magnetometer, namely, 64 seconds. Some parameters, such as the solar wind speed  $V_{sw}$ , are averaged only every 320 seconds.

We model the bow shock as described earlier; the actual location of the subsolar point depends on the solar wind conditions in each averaging interval. A sampling effect arises because in 64 sec., the solar wind plasma typically covers about  $4 R_E$  in the minus-X direction. The shock structural pattern does not therefore consist of a single Q-perp/Q-par division, as in either example of Figure 4, but a series of circular bands about  $4 R_E$  thick, each with its own division, that work their way downwind along the shock as time progresses.

Figure 5 is one computer sketch from the animation sequence. At the time of this interval, the IMF had an above-average sunward component, typically  $B = (-3, 1.5, -.5)$ , causing most of the nose of the shock to be quasi-parallel, the quasi-perpendicular section being largely along the eastern flank. The view is from SWC latitude and longitude  $15^\circ, 30^\circ$ , with the solar wind blowing away from the viewpoint toward the upper left. Several important features of our viewing procedure are seen in the figure: First, the sampling-bands are apparent, both in Q-perp and Q-par symbols; second, the bands and Q-par tildens together may form unintended Moire patterns that a more sophisticated symbolism will be necessary to remove; third, the edges of some bands can overlap slightly, because each new solar wind sample, several bands wide, can require its shock section to move in or out or rotate slightly with a new direction of  $V_{sw}$ ; fourth, the B-X cross sections can be discontinuous at band edges, particularly noticeable where the geometry is Q-perp, because each 64 sec. average of the IMF may have a quite different orientation from its adjacent averages.

We defer discussion of a fifth feature to a later paragraph, but we elaborate here on the bands in Figure 5 is an accident of the averaging interval available to us in creating our first sketches. Presumably, the

higher the time resolution of the samples used as input to the program, the narrower the bands and the more continuous would be the lines drawn on the shock surface, with any signs of discontinuity disappearing in the limit of continuous sampling. Each sketch would then have much higher quality and much greater resemblance to reality. Each sketch would also take much longer to compute and much longer to plot, and production of an animation sequence would become a lengthy, tedious, and expensive undertaking. Our initial effort therefore represents a compromise among many factors.

#### TECHNOLOGICAL STATISTICS.

Each multiband computer sketch takes about 9 minutes to make on the CRT display and 11 minutes on the X-Y color-pen plotter. Our first film consists of 145 images representing two hours and 35 minutes of data, compressed into 1.5 minutes of viewing time. All sketches are made on transparent acetate animation cells and photographed over another cell underneath containing the axes alone. We thus save computer time by not redrawing the axes with each sketch, except when changing the direction in space from which we imagine the shock is being viewed. This direction is changed from time-to-time both to clarify the structural picture at the curved edge of the shock image and to add variety to the sequence. We shoot 15 frames of 16mm film of each sketch, for projection at 24 frames/sec., so each image is projected for .625 sec. and represents 64 sec. of averaged data.

#### DISCUSSION.

Graphic modeling of plasma boundaries and plasma processes in space should serve both as a means of testing the models used and of revealing features implied by the models that would otherwise escape attention. Even instantaneous, or static, images, when offering the wealth of detail or comprehensive summary made possible with computer assistance, should yield fresh insights. Figure 5 illustrates some of this potential.

A fifth prominent feature of the shock image in Figure 5 is the irregular boundary between Q-par and Q-perp sections of the surface. This arises from the combination of continual change in the IMF and the finite speed at which fresh solar wind moves downstream. The result is sections of Q-par structure surrounded by section of Q-perp structure, or the reverse, so that the dividing boundary may have intrusions, or "fingers" of opposite structure extending either direction across the "average" boundary curve. As time advances, these intrusions work their way downwind along the shock and out to the flank and are replaced by new ones in a new pattern. In the upper and lower right of Figure 5 we see alternating fingers of Q-par and Q-perp symbols. Thus the structure of a given point of the shock near the division may vary even though the overall orientation of the IMF remains fixed on average. Further, the nature of the local foreshock at an observation point upstream will vary accordingly; as the source region for the observation point varies in location and structure at the shock, return ions and ULF waves will appear in bursts, especially reflected beams and intermediate ions and transverse waves associated with the Q-par/Q-perp transition. This, of course, is exactly what is commonly recorded by satellite instruments upstream.

Note that even though the sketch of Figure 5 is static, the phenomenology we have been describing appears only because the image is taken as one of a sequence of several drawn according to a stream of actual data. We believe that far more valuable inferences will ensue from viewing the entire sequence in rapid order as an animation movie. We began with the intent of creating a pilot that would simply improve, through animation, our picture of the global character of the effect if IMF changes on the bow shock; changes which we already understood. It appears already that we may in fact

be producing mediocre animation but dramatically better physics by revealing the kind of boundary details just described. We are certainly persuaded that a few years hence, data display through animated computer-graphics will be a routine analytic procedure.

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#### Acknowledgements.

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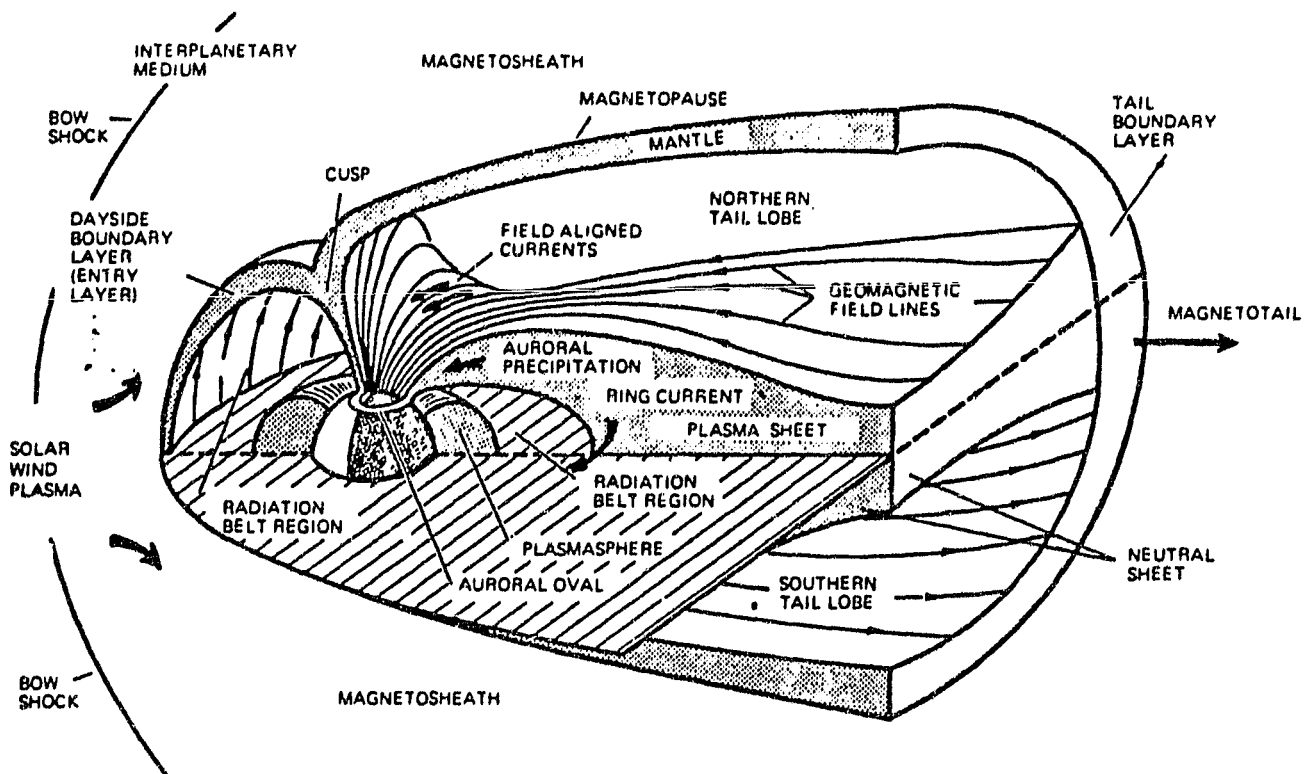


Figure 1. Schematic view of the magnetosphere, showing some of its major features (not to scale).

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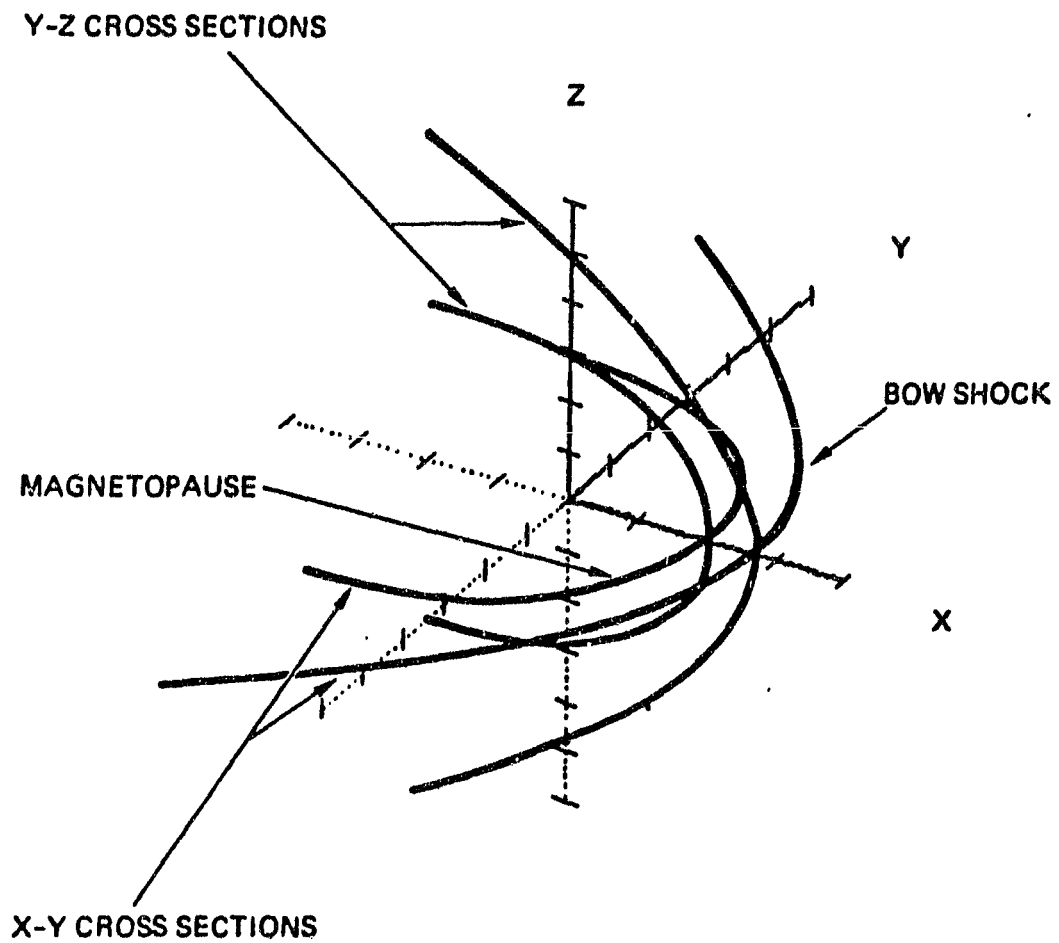


Figure 2. Computer sketch of the magnetopause enclosed by the bow shock.



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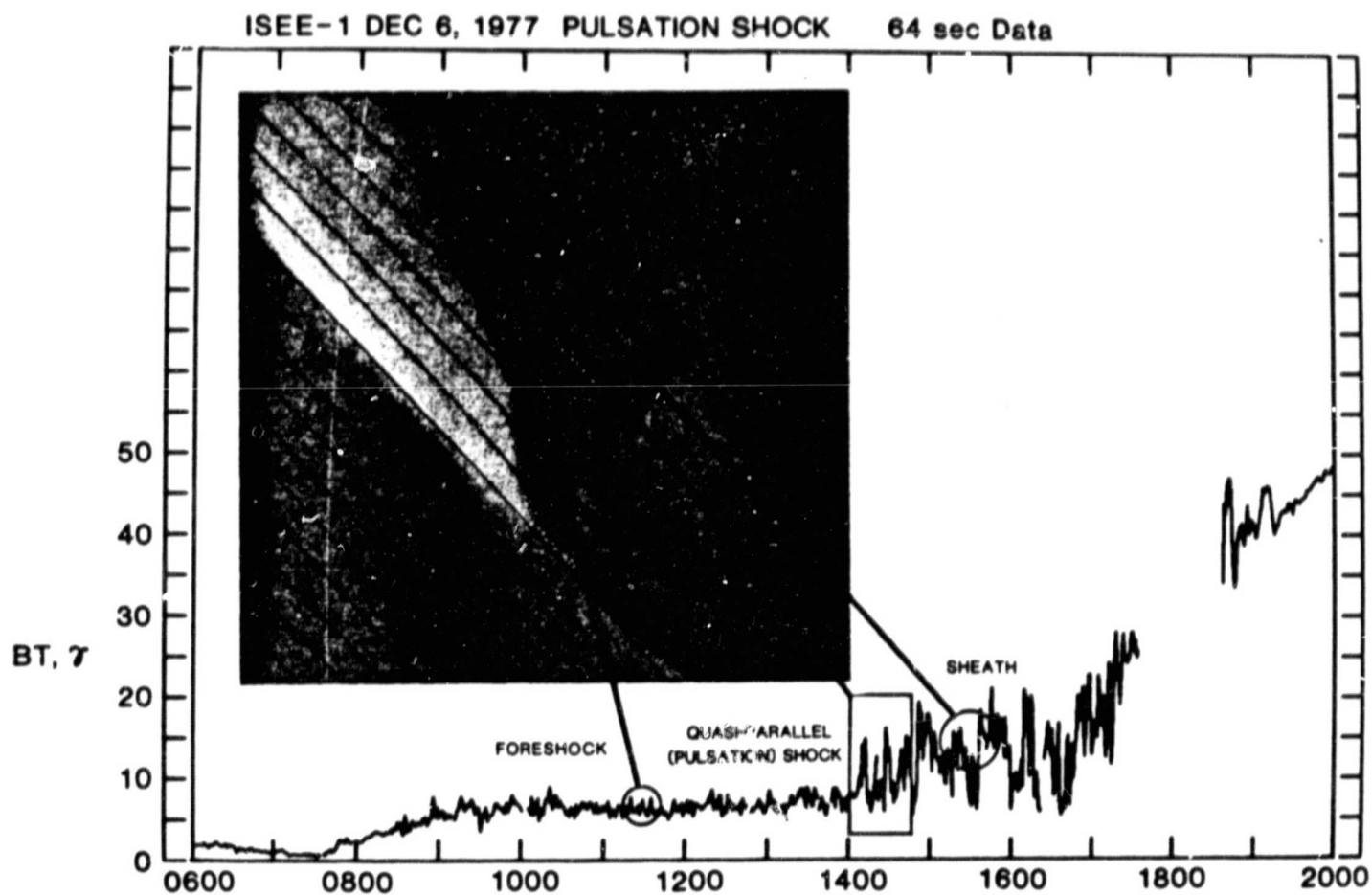


Figure 3. Schematic cross section of the bow shock and foreshock (insert) related to the magnetic profile observed during a satellite passage through the quasi-parallel (pulsation) shock structure.

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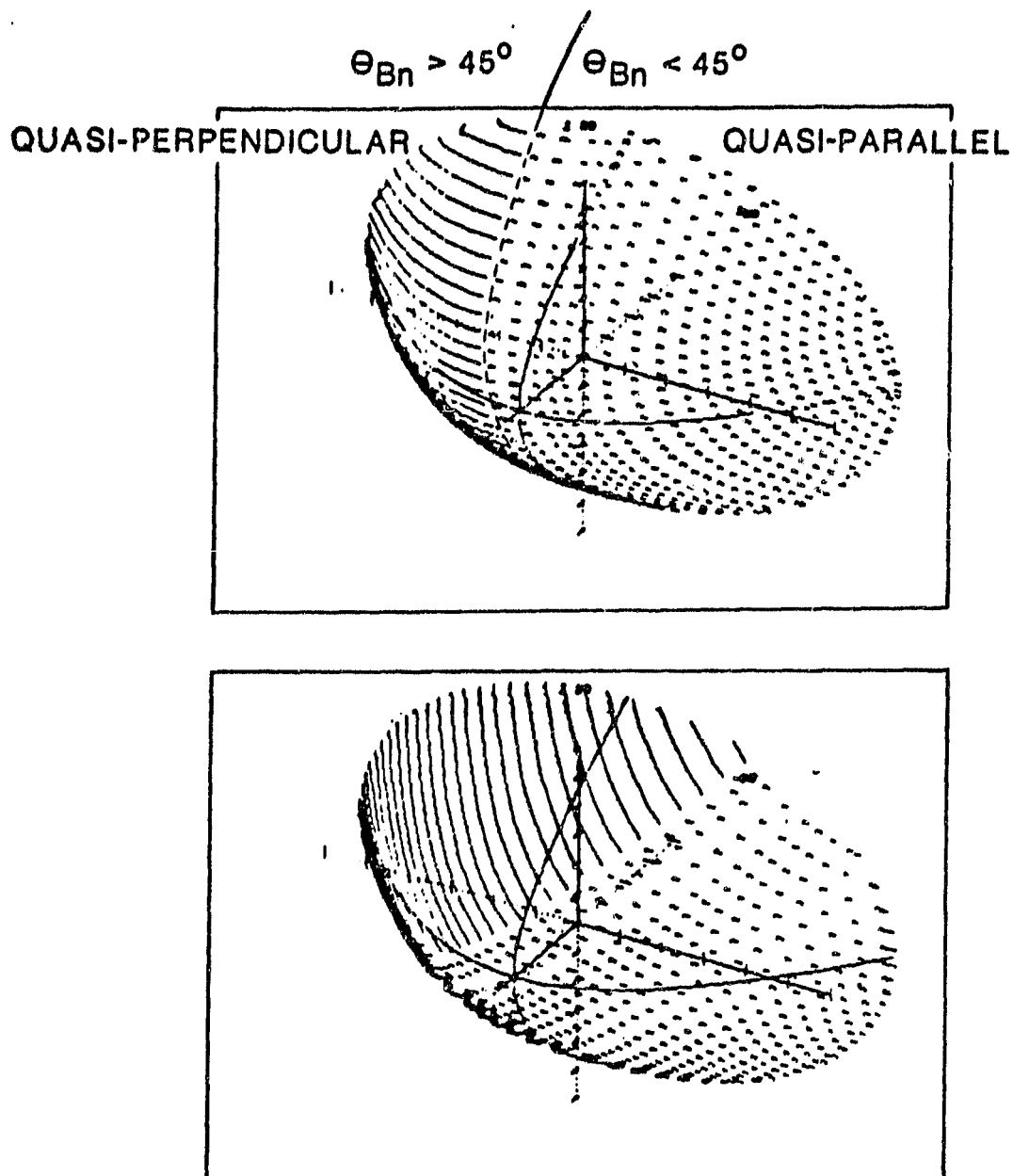


Figure 4. Two views of Earth's bow shock for different orientations of the IMF showing the rearrangement of quasi-perpendicular and quasi-parallel sections.

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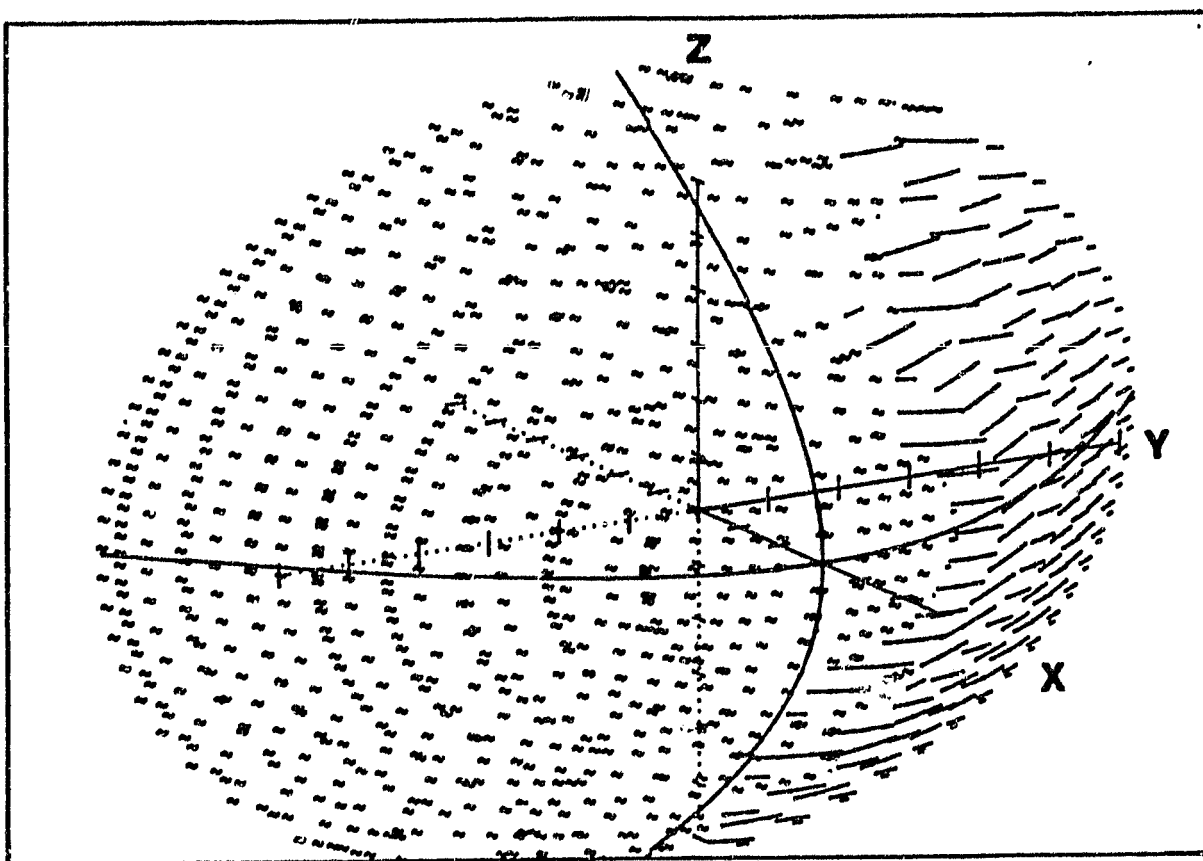


Figure 5. A single computer-generated shock-structure diagram selected from a sequence of such diagrams determined by a sequence of sampled solar wind parameters.

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Magnetospheric Boundaries

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APPENDIX III

## Introduction

The quadrennium has seen an explosive growth in our knowledge and understanding of the various plasma and magnetic field boundaries in the terrestrial magnetosphere. Nowhere is that more evident than at the magnetopause and bow shock. In the 1975 and 1979 quadrennial reports the magnetopause was covered in a single paragraph each year. The bow shock received one paragraph in 1975 and none in 1979! The reason for the resurgence of interest in these boundaries was the availability of new and exciting measurements from the ISEE-1 and -2 spacecraft. Not only did these spacecraft carry sensitive high-time resolution, three-dimensional plasma instrumentation as well as high-time resolution and accurate magnetic and electric field data, but also the variable separation of the two spacecraft allowed the velocity of structures to be measured and thereby allowed time profiles to be converted to spatial profiles. Simultaneously, numerical simulationists were benefiting from larger and faster computers and the development of ever increasingly sophisticated codes. During this period the simulation field began to blossom. The combination of good data and realistic models led to not only empirical knowledge but theoretical understanding of many of the processes at work.

Progress in the field was aided by many workshops and conferences devoted to the magnetospheric boundaries. The first of these, the Chapman Conference on Magnetospheric Boundary Layers, held in Alpach Austria in June 1979 covered mainly the magnetopause and boundary layer. The proceedings of this conference has been published as an ESA special publication, SP-148. There were two coordinated data analysis workshops, CDAW-3 and CDAW-4, devoted to the bow shock and the magnetopause as observed by ISEE-1 and -2. These have been described by Ogilvie (1982) and Paschmann (1982), respectively. The latter workshop spawned a series of papers in a special issue of the Journal of Geophysical Research (April, 1982). A Gordon

Conference on collisionless shocks was held in June 1981 but as is their policy no proceedings were published.

In this review we will proceed from the outside in. We will discuss first the bow shock and foreshock and say a little about interplanetary shocks. Then we discuss the magnetosheath, magnetopause and boundary layer. After a section on reconnection we treat the plasma and neutral sheets, polar cusp and the injection of plasma into the inner magnetosphere.

## GENERAL

The interval 1979 through 1982 spanned the transition from exploratory work with preliminary data from ISEE-1,2, and 3 [Bane et al., 1979; Russell and Greenstadt, 1979; 1981] to detailed investigations with fully calibrated and updated measurements from these satellites. Published contributions therefore included the last of the ISEE preliminary papers, announcements of new discoveries, and follow-up accounts of shock phenomenology,--plus reports based on Voyager and Pioneer-Venus data.

Broadly speaking, studies have divided themselves into two categories: careful documentation of more or less anticipated features of the shock using the high-quality instrumentation and two-point measurements of the ISEE-1,2 spacecraft, and intensive investigation of the (quasi-parallel) foreshock inspired by the discovery of the array of return ion distributions reported in the last IUGG interval (Gosling et al., 1978). Both categories have benefited from reawakened interest in, and support of, theoretical calculations and large-scale computer simulations of shock and foreshock phenomena. As might be imagined, documentation is proceeding slowly because of the care required in quantifying shock features reliably and because of frequent diversion of a limited number of researchers to the exciting area of foreshock dynamics.

Because of the collaborative nature of ISEE projects, it is difficult to separate national from international reports. We adopted the rule of including here only papers whose first author was in a U.S. institution; a glance at the bibliography will show it to be lengthy enough. No review of this period's accomplishments would be complete without explicit mention of the special issue of the Journal of Geophysical Research: ISEE Upstream Waves and Particles, Vol. 86, No. A6, June 1, 1981, which contains many of the articles cited here, including the excellent overviews by Tsurutani and Rodriguez [1981] and Kennel [1981].

Figure 1 illustrates conceptually the items of shock structure that have been the principal foci of activity to the present. Fig. 1 is an adaptation of a sketch used in an earlier review prepared at the beginning of this IUGG interval; the hatched areas indicate those combinations of shock geometry and structure that have been the subjects of intense and detailed investigation. We see that substantial areas of the figure are unshaded, and that only a minor fraction of the shock's features have been studied. Nevertheless, much has been learned and a substantial foundation for continued study has been laid.

## HYDROMAGNETIC MODELING

Refinement of bow shock location and shape continued with efforts to compare measurements and models at the terrestrial planets [Slavin and Holzer, 1981; Slavin et al., 1982], and the analytic description of the bow shock system was advanced by Zhuang and Russell [1981] in a

comprehensive study of magnetosheath thickness. Encounters with the Jovian bow shock were described by Lepping et al. [1981].

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#### BOW SHOCK FRONT OR THERMALIZATION LAYER

By either term above we mean that feature of the shock wherein a substantial portion of the solar streaming energy of any plasma component is converted into thermal, although not necessarily isotropic or maxwellian, energy. The thicknesses and the diagnostics by which the layer is defined, as well as the kinetic details of the conversion are the subjects of inquiry.

An overview of the "typical" quasi-perpendicular shock was given by Greenstadt et al. [1980], in which the relationships of the various diagnostics to each other could be seen at medium resolution by current standards. Rapid heating of electrons in the magnetic foot and ramp of the shock was apparent, along with generation of a secondary distribution of accelerated protons, while thermalization of both proton distributions was seen to occur through a more prolonged series of magnetic oscillations behind the principal shock ramp and overshoot. The overshoots themselves were studied by Russell et al. [1982] and Livesy et al. [1982], who found that the overshoots grow with mach number above critical ( $M > 3$ ); this result is consistent with that of simulations showing the association of overshoots with trapped, reflected particles constituting the secondary distribution of protons present in the shock front above  $M \sim 3$  [Leroy et al., 1981; 1982].

High resolution views of electron heating at the bow shock were described by Bame et al. [1979]. Further details of electron distributions typical of the q-perpendicular shock have been displayed by Feldman et al. [1982]: Electron distributions are skewed and anisotropized by the shock potential, producing distribution envelopes with "bumps", i.e. free-energy components defined by nonmonotonic  $df/dE$ , offset toward or away from the shock, depending on location up- or downstream. Such distributions can be expected to excite the plasma instabilities responsible for thermalizing the particles, as elaborated in the Feldman et al. paper. A careful analysis of the energy gain of electrons in the observed reference frame has been undertaken by Scudder and Goodrich [1982], and an extensive treatment of microinstabilities in the bow shock has been prepared by Wu et al. [1982].

The general picture of quasi-perpendicular shock structure has been enhanced by a description of the variable plasma wave turbulence at different planetary shocks, where a progressively more distinct spectral peak between the Buneman and ion plasma frequencies was found in going from Venus to Saturn [Scarf et al., 1981]. It was speculated that this progression followed the increase in Mach number with distance in the solar wind away from the sun. At an opposite extreme, Russell et al. [1982] have been attempting to analyze Earth's bow shock in its simplest form at low Mach number and low beta. They find that laminar, quasi-perpendicular shocks defined by these conditions have thicknesses close to the ion inertial length  $c/\omega_{pi}$  and that thickness increases as  $\theta$  drops toward 55 deg. Figure 3 sketches the rough dependence of Q-perpendicular shocks on Mach number and angle.



Study of quasi-parallel shock structure is progressing very slowly. A great deal of data have been examined, but almost nothing has been published that doesn't center on the associated foreshock, reviewed separately below. The first quantitative attack on Q-parallel structure was reported by Greenstadt et al. [1982], who computed the correlation between large-amplitude pulsations at ISEE-1 and ISEE-2 at the outer edge of the shock structure, finding a sharp drop from high to low correlation at a satellite-separation of about 1000 km. The drop appeared to be compatible with Larmor radii of protons typically observed in the foreshock just upstream from the outermost pulsations.

Figure 2 summarizes, by shading portions of a familiar table of structural designations, the types of shock structure where the principal activity has been taking place.

#### FORESHOCK

**PARTICLES.** Starting with the well-defined, energy-dependent electron boundaries found near the field line tangent to the bow shock [Anderson et al., 1979], foreshock, i.e. return, particles have commanded major attention. The distinguishable distributions of 1-40keV return ions discovered earlier--beams, diffuse, and intermediate [Gosling et al., 1979]--have been tied by simultaneous IMF directions to Q-perpendicular, Q-parallel, and transition shock structures, in the same order [Greenstadt et al., 1980]. The distributions have been characterized in phase space [Eastman et al., 1981; Sentman et al., 1981; Gurgiolo et al., 1981], and the deceleration of the solar wind by diffuse distributions has been noted [Bame et al., 1980]. At last, theoretical instability computations have been performed using realistic ion and electron distributions in the solar wind [Gary, 1981; Gary et al., 1981; Sentman et al., 1981; Feldman et al., 1982], and consequences of these are being tested with further data.

Additional interest has centered on higher energy return protons in the 40keV to 1MeV range, particularly on their detection and occurrence far upstream at ISEE-3 [Anderson, 1981; Gloeckler, 1979; Ipavich et al., 1979; 1981; Sanderson et al., 1981]. Anisotropies and spectral shapes of these ions, together with their link to the quasi-parallel bow shock via correlation with the appropriate IMF directions, have awakened interest in seeking observational evidence near the earth's shock that cosmic rays can be fashioned out of the plasma background by reflection, or at least ejection, from relatively weak shocks like the earth's. Association of 40keV and 30MeV protons with interplanetary shocks [Gosling et al., 1980; Evans et al., 1982], most of which are even weaker than the earth's at 1AU, have strengthened this interest, to be discussed again in a later paragraph.

**WAVES.** Although foreshock waves are derived from interactions of foreshock particles with the solar wind, they were the phenomena from which the foreshock was originally defined, because of their ease of detection and processing compared to backstreaming particles. Waves have continued to be the pioneer tool in investigating upstream effects. In particular, they have served to demonstrate the existence of foreshocks of other planets. Hoppe and Russell [1981] showed the universality of the various foreshock ULF waves at Mercury, Venus, and

Jupiter, including discrete wave packets and the incipient shock-like wave gradients underlying them at Venus. Indeed, the dependence of upstream wave periods on IMF magnitude at Earth [Russell and Hoppe, 1981] was extended to a common relationship for the waves at four planets, implying resonance with beams of ions of essentially the same energy at each of the planets, and perhaps in other astrophysical systems as well [Hoppe and Russell, 1982a]. The wave foreshock concept was also extended to interplanetary (IP) shocks, where VLF electromagnetic and plasma waves were found to precede IP shocks for many hours ahead of actual shock arrival if the local geometry was Q-parallel with respect to the IMF overtaken by the front [Kennel et al., 1982; Greenstadt et al., 1982].

Wave properties in the earth's foreshock were also explored further. Wave packets attached to the largest amplitude ULF waves were found to be whistlers by correlating ISEE-1 and -2 data [Hoppe and Russell, 1980], and small waves in the foot of a Q-parallel shock, a "miniforeshock", so to speak, were shown to be consistent with phase and group velocity properties of whistlers in the local solar wind [Greenstadt et al., 1981]. Upstream plasma waves were described by Filbert and Kellogg [1979] and Gurnett et al. [1979].

PARTICLES AND WAVES. The physics of the foreshock lies, of course, in neither particles nor waves, but in the relationships between them. Fundamental to these relationships is the correspondence between particle and wave types [Hoppe et al., 1981; 1982a], according to which beams, intermediate, and diffuse ion distributions are associated respectively with small, 1Hz whistlers, larger transverse narrow band, .1-.01Hz waves, and still larger ( $\Delta B/B/2$ ), compressional, .1-.01Hz waves and connected whistler-wave packets. Figure 4, from Hoppe and Russell [1982b] summarizes this correspondence. Instabilities caused by beams [Gary et al., 1981] and diffuse distributions [Sentman et al., 1981a] have been proposed to explain the associated waves, as mentioned earlier, but neither theory has correctly provided all the observed properties of the waves. In any case, skewed foreshock electron distributions offer a better and more likely explanation for the 1Hz waves than the ion beams [Feldman et al., 1982b], which are not always seen with these waves [Hoppe et al., 1982]. In the VLF range, narrow banded, ion acoustic waves are associated with backstreaming protons under about 1.5keV, while electron plasma oscillations, whistlers, ion acoustic waves, and low frequency electrostatic waves accompany electrons between .2 and 1.5keV [Anderson et al., 1981]. The upstream plasma waves are closely allied with spatial gradients of foreshock particles and bursts of wave noise appear at the edges of particle enhancements [Anderson et al., op.cit.; Parks et al., 1981].

Among the most exciting results has been the development of both theory and observation of the higher energy, 40keV-1MeV, protons. These have been treated by Monte Carlo simulation [Ellison, 1982] and as products of a Fermi process in which the upstream ULF waves serve as reflecting and scattering centers, together with the shock downstream, to produce incipient cosmic rays. A self-consistent model of ion energization using reflected beams as feedstock to generate waves, which in turn reflect and scatter the ions until they leave a "free escape" boundary beyond 10 or 20 Re upstream from the Q-parallel shock [Lee et al.,

1981; Lee, 1982], has succeeded in predicting energy spectra consistent with measured distributions [Ipavich et al., 1981].

#### INTERPLANETARY SHOCKS

The growing theory and evidence that energetic ions are produced out of the thermal plasma by the earth's bow shock has stimulated fresh attention to IP shocks, where suprathermal particles, both electrons [Potter, 1981] and ions [Cosling et al., 1980] have been recorded, along with precursor plasma wave noise that might be indicative of forward particle escape [Kennel et al., 1982]. The structure of IP shocks has enjoyed renewed scrutiny [Pesses et al., 1979; 1981; Russell and Greenstadt, 1981], and an interesting instance of bidirectional electron streaming suggestive of closed field lines in the driver gas has been described [Bane et al., 1980]. Finally, coronal transient phenomena have been reviewed generally by Dryer [1982], and the interaction of IP shocks with the bow shock, magnetosheath, and magnetopause have been modelled and observed Zhuang et al. [1981; Winterhalter et al. [1981].

#### MAGNETOSHEATH

As usual, the magnetosheath has been the focus of massive inattention relative to other shock-related subjects, with a few notable exceptions. Crooker et al. [1981] compared the appearance of energetic ions in the sheath with IMF orientation to produce patterns of these ions downstream. Because of the known correlation of the ions with enhanced magnetic sheath turbulence, ion patterns probably approximated the patterns of downstream Q-parallel structure, or so the comparisons suggest: IMF across the solar wind flow removed the ions to the outside flanks of the sheath; stream angle IMF placed them mostly in the morning sheath; IMF parallel to the solar wind filled the subsolar sheath with energetic ions. Figure 5, from the Crooker et al. paper, illustrates these configurations. The possibility that ~~transferred~~ magnetospherically ~~trapped~~ ions may provide some of the energetic ions found in the sheath was argued by Spiser et al. [1982], and a generation mechanism for lion roars in the sheath was proposed by Thorne and Tsurutani [1981].

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### MAGNETOPAUSE

The amount of research done on the magnetopause over the last few years has been great and we cannot do it justice in the space provided here. Readers interested in further details are referred to the various excellent reviews available. Fairfield (1979) summarizes work on the magnetopause prior to the ISEE results. Paschmann (1982) provides an up-to-date review of the ISEE results and Sonnerup (1979) reviews the theory of reconnection which is a key process at the magnetopause. Finally, Cowley (1982) provides a detailed and up-to-date review of reconnection at the magnetopause, flux transfer events, and the boundary layer in the guise of examining the causes of connection.

Location. There is very little work being done on the average location and shape of the magnetopause at present. However, magnetopause motions are still of quite some interest. One of the puzzles about the shape of magnetopause was why it appeared to be symmetric despite the fact that  $\underline{J} \times \underline{B}$  forces would cause an additional deflection of the post shock solar wind. Zhuang et al. (1981) developed an analytic model of the magnetosheath to examine this problem and found that, while the flow deflection did take place in front of the magnetosphere, the thermal and magnetic pressure of the magnetosheath maintained a nearly symmetric magnetosphere.

The interaction of interplanetary shocks with the magnetopause was examined by Grib et al. (1979) and Zhuang et al. (1981). The observed response of the magnetopause to shocks was well explained by these models. Another cause of magnetopause motion was examined by Crooker and Siscoe (1979). They found that substorms caused large excursions of the tail magnetopause.

One postulate that has attracted some vociferous support but little experimental evidence is that of impulsive injections through the magnetopause (cf. Heikkila, 1979, 1982a). The advocates of this model suppose that over dense regions or blobs

in the solar wind are blown against (and through) the magnetopause. These models ignore the fact that the stagnation streamline paints the entire magnetopause. The subsolar magnetosheath spreads the normal stresses over the entire magnetopause.

Gasdynamic simulations of the solar wind interaction with the magnetosphere have been available for many years, but only recently have there been magnetohydrodynamic models. Most recently these models have developed in three-dimensions (Leboeuf et al., 1981; Wu et al., 1981). Presently they do little more than determine the location of boundaries and the flow field and field line geometry around the obstacle but even this is useful especially at low Mach numbers where the gasdynamic solutions are expected to be inappropriate.

Motion and Structure. The earliest ISEE measurements revealed the magnetopause to be in irregular and constant motion (Russell and Elphic, 1978; Paschmann et al., 1978; Elphic and Russell, 1979). As shown in Figure 6 the velocities ranged from kilometers per second to hundreds of kilometers per second (Berchem and Russell, 1982) but the thickness was much more constant at about 400-1000 km or a few ion gyro radii. One of the surprises of the magnetopause was the variation in structure in short distances along the boundary. During a rapid interplanetary shock-induced motion of the magnetopause the currents on the magnetopause were very significantly different on a scale of only 300 km (Winterhalter et al., 1981).

The structure of the magnetopause cannot be simply described in terms of MHD discontinuities. Although occasionally the magnetopause has the magnetic and plasma signatures of a rotational discontinuity (Paschmann et al., 1979; Sonnerup et al., 1981), it also can be found with a clear tangential discontinuity signature even though the magnetosheath and magnetospheric fields are antiparallel (Papamastorakis et al., 1982). Contrary to common belief the magnetic field

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rotation is not controlled by the gyration of ions or electrons so that it follows a particular path dependent on the sign of the normal component of the field crossing the boundary. Rather the path the magnetic field follows from the magnetosheath to the magnetosphere is the shortest path (Berchem and Russell, 1982b). Computer simulations have been performed of both the tangential discontinuity and rotational discontinuity by Lee and Kan (1979; 1982). These originally favored the electron polarization but recent simulations (Swift and Lee, in preparation, 1982b) reproduce these new observations.

Flux Transfer Events. Frequently when ISEE-1 and -2 are near the magnetopause, the magnetic field will oscillate in a manner that resembles that occurring during a magnetopause crossing but with some significant differences. These differences suggest that a tube of magnetic flux in the magnetosphere has reconnected with some magnetosheath magnetic field and is being pulled tailward (Russell and Elphic, 1978, 1979; Elphic and Russell, 1979). A sketch of the configuration of an FTE is shown in Figure 7. During these events the low energy plasma resembles the magnetosheath plasma and the energetic particles resemble the magnetospheric population. Daly et al. (1981) have shown that the energetic ions are streaming out of the magnetosphere. The electron signature is, however, more confusing. These results were confirmed by Scholer et al. (1982). Paschmann et al. (1982) has examined the overpressure in the flux transfer event and find that it is equal to the Maxwell stress imposed by the twist and draping of the magnetic field around the tube. Modeling the leakage of particles out of the magnetosphere through an FTE has shown that the ISEE observations can easily be replicated thus lending further support to the FTE interpretation (Speiser and Williams, 1982). Initially all FTE's had the same signature in the component of the magnetic field normal to the magnetopause, outward then inward. However, Rijnbeek et al. (1982) have discovered reversed FTE's on

August 9, 1978 a period when Sonnerup et al. (1981) showed that ISEE was probably observing steady-state reconnection below the merging line. This is very important for two reasons. First, it shows that the sign of the FTE signature reverses from north to south across the merging line. Second, it shows that the magnetosphere may be undergoing steady-state reconnection and patchy reconnection simultaneously or nearly so. The statistical accuracy of these results have been extended using three years of data by Berchem and Russell (unpublished manuscript, 1982) who show that the magnetospheric equator essentially divides the FTE signatures into two groups, normal and reversed. This pattern is consistent with FTE's being created by reconnection at the magnetospheric equator and then being pulled poleward away from the equator by field line tension and magnetosheath convection.

Remote Sounding of the Magnetopause. Williams (1979, 1980) and Williams et al. (1979) note that the near presence of the magnetopause is associated with gyro phase asymmetries in the 3-D energetic ion observations. In other words, particles which intersect the magnetopause (or some boundary near the magnetopause) in their cyclotron motion about a field line appear to be lost. While Williams and coworkers originally identified this boundary with the magnetopause, it need not be so. It is perhaps more correct to call it the trapping boundary which could, for example, be the boundary between open and closed field lines. This technique has also been used to measure magnetopause velocity (Fahnenstiel, 1981; Fritz and Fahnenstiel, 1982; Fritz et al., 1982) but because the technique, at least as applied to ISEE-1 data, returns a magnetopause location once every 30 seconds care must be exercised in the interpretation of the data.

Boundary Layer. The boundary layer is perhaps the outstanding enigma of the magnetosphere. It is a region of density and temperature intermediate between that of the magnetosheath and that of the magnetosphere just inside the magnetopause. The thickness of the boundary layer is extremely variable (Eastman and Hones, 1979).

It also often is flowing away from the sun but occasionally flows the other way. Sonnerup (1979, 1980) has developed a simple model of a viscous boundary layer coupled to the earth by field-aligned currents. Field-aligned currents certainly are present but they don't obey the simple Sonnerup model (Sckopke et al., 1981; Hones et al., 1982). In fact, the boundary layer studied by Sckopke et al. (1981) seems to be associated with the magnetospheric roots of flux transfer events (Cowley, 1982). This should not be surprising since Paschmann et al. (1982) find that flux transfer events in the magnetosheath contain a mixture of magnetosheath and magnetospheric plasma having temperatures higher and densities lower than the magnetosheath. Such properties are very similar to those of the boundary layer. Reiff (1979) has reviewed the properties of what is thought to be the low altitude extension of the boundary layer. The low altitude measurements reveal two distinct plasma populations on the dayside: one predominantly on open field lines with low electron temperature ( $\sim 15$  eV), decreasing proton energy with increasing latitude and correlated with the IMF; the other on closed field lines with a V-shaped ion distribution and an electron temperature of about 50 eV warmer than the above layer but cooler than the plasma sheet.

Miscellaneous. A very attractive postulate about the location of the merging line was put forth by Crooker (1979a,b; 1980) who assumed that merging was most likely to occur at those places on the magnetopause where the magnetospheric and magnetosheath fields were exactly antiparallel. The resulting merging line depended on the relative orientation of the magnetospheric and magnetosheath magnetic fields and was in the equator and passed through the subsolar point only when the interplanetary magnetic field was exactly southward. Otherwise the merging line was at high north and south latitudes. However, observations of steady-state merging (Sonnerup et al., 1981) and FTE's as discussed above support a near equatorial merging line at all times.



If reconnection is taking place, the plasma flows into the magnetopause from both the magnetosheath and the magnetosphere. This is equivalent to a tangential electric field. Such a tangential electric field has been reported by Mozer et al. (1978, 1979) and Fahleson et al. (1979) using ISEE-1 measurements on November 20, 1979. However, this was a very turbulent period with extremely violent and irregular magnetopause motion. Heikkila (1982) has pointed out that these variations cause inductive effects in the data so that the interpretation of the measurements is not as simple as first believed.

Most of the work on the energetic electron layer which surrounds the magnetopause was done prior to the ISEE results (Bieber and Stone, 1979; Meng, 1979). (Scholer et al. 1982b) have examined high resolution energetic electron measurements for one ISEE pass through the subsolar magnetopause. They find a very filamentary structure with scale size of a few electron gyro radii. Ion composition measurements have been performed in the boundary layer, magnetopause and adjacent magnetosheath (Peterson et al., 1982). All three regions contain both ionospheric and solar wind components. Plasma waves are intense near the magnetopause (Gurnett et al., 1979; Tsurutani et al., 1981; Anderson et al., 1982). In flux transfer events, the dominant plasma wave features are an intense low frequency continuum a dramatic increase in the frequency of occurrence of short wavelength spikes, quasi-periodic electron cyclotron harmonics correlated with  $\sim 1$  Hz magnetic field fluctuations and enhanced electron plasma oscillations (Anderson et al., 1982).

RECONNECTIONORIGINAL PAGE IS  
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There has long been little doubt that reconnection as described by Dungey (1961) is an important process in the magnetosphere (cf. Russell, 1976). However, until the launch of ISEE, the existing plasma data lack sufficient time resolution and 3-D coverage to monitor the variations in plasma behavior predicted in a reconnecting magnetopause. As expected ISEE-1 and -2 soon encountered the expected signatures of merging or reconnection in the plasma data (Paschmann et al., 1979) as shown in Figure 8. However, the quasi-steady state merging signature was only clearly found 11 times in two seasons of observations (Sonnerup et al., 1981). On the other hand, when conditions are right, the reconnection process can proceed continually for many hours (Gosling et al., 1982). Further, some of the reconnection must be taking place in an unsteady manner in FTE's. On the other hand, Papamastorakis et al. (1982) show that reconnection doesn't always occur when you might expect it to.

Eastman and Frank (1982) have questioned Paschmann et al.'s (1979) identification of reconnection. Their criticism in turn has been examined in detail by Scholer et al. (1982) and Daly and Fritz (1982), and successfully countered by the latter two authors.

Despite the success of ISEE observations in demonstrating the reality of reconnection, there still remains the problem of understanding how it operates and what controls it. This problem is being attacked not just through observational programs but also through analytic theory (Coroniti, 1980; Greenly and Sonnerup, 1981; Quest and Coroniti, 1981a,b), computer modeling (Cheng, 1979; Sato and Hasegawa, 1980; Birn and Hones, 1981; Brecht et al., 1982; Matthaeus, 1982; Sato and Walker, 1982) and laboratory studies (Geckman and Stenzel, 1981; 1982; Stenzel and Geckman, 1981, 1982; Stenzel et al., 1982; Baum and Bratenahl, 1982). The experiment of Baum and

Bratenahl is directed more to dayside reconnection, whereas the experiment of Stenzel, Gekelman and co-workers is more appropriate to the magnetotail. The latter experiment has yielded a rich harvest of results including the observation of double layers in the current sheet of the reconnecting plasma.

If reconnection occurs on the dayside, then reconnection must also occur on the nightside of the magnetosphere also because dayside reconnection if left unchecked and unreplenished would drive all the magnetic flux into the magnetotail. Observations in the tail assure us that indeed reconnection takes place there. Caan et al. (1979), Hones and Schindler (1979), Hones (1980), Nishida et al. (1981) and Hayakawa et al. (1982) observe the expected joint field and plasma behavior. Beiber and Stone (1980; 1982) observe the expected streaming electrons and plasma behavior. Forbes et al. (1981a,b) observe the tailward retreat of the plasma sheet and the expected plasma sheet drift. There can be little doubt from the in situ tail data that reconnection is also occurring there.

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PLASMA SHEET AND NEUTRAL SHEET

The magnetotail is extremely important in magnetospheric physics as the site of energy storage for substorm related processes. Thus, some of the tail related papers will be discussed in the reviews of Burch (this issue, 1982) and Hughes (this issue, 1982). However, some of these works merit the risk of repetition. Fairfield et al. (1981a) combined IMP-6 field and plasma data to study the accumulation and release of energy in the tail. Coroniti et al. (1980) combined IMP-7 plasma, field, energetic particle and plasma wave data to take a detailed look at plasma sheet behavior during substorms. Rapid flows and highly turbulent fields were observed. Erickson and Wolf (1980) question on theoretical grounds whether steady-state reconnection is even possible in the tail. Hones et al. (1982) report observations of the three-dimensional plasmoid that is formed during reconnection in the tail.

The neutral sheet has long been known to be pulled north and south by the diurnal wobble of the earth's magnetic equator as if the neutral sheet were hinged to the magnetic equator at about 10 Re. Fairfield (1980) has used IMP tail observations to refine the model of how the neutral sheet responds to this diurnal torquing.

Hardy et al. (1979a) have examined the plasma mantle and boundary layer plasma as seen in the surface of the moon with the suprathermal ion detector experiment. They find that the appearance of these ions is controlled by the interplanetary magnetic field. The probability of appearance is greater for southward fields and in the northern lobe is greater on the dawn side of the tail when the solar magnetospheric Y-component of the IMF is positive. In the south a positive Y-component increases the probability in the dusk sector. Closer to the earth Fairfield et al. (1981) report that the plasma sheet can become as thin as 1000 km during substorms.

The energetic ion composition of the plasma sheet has been investigated by Peterson et al. (1981). They find that the plasma sheet has a variable ionospheric component representing from 10% to more than 50% of the total number density and that there must be more than one process responsible for the energization of solar wind plasma to plasma sheet energies.

A thin layer of earthward streaming energetic protons alpha particles has been observed by several groups just external to the plasma sheet (Mobius, 1980; Spjeldvik and Fritz, 1981; Williams, 1981). The layer appears to be about two gyro radii thick and can be seen to reflect from the earth and stream tailward. Another important observation in this same region of space is the detection of large electric field spikes (up to  $\sim 80 \text{ mV m}^{-1}$ ) usually within one minute of the plasma sheet boundary (Cattell et al., 1982). These strong electric fields occur in regions of enhanced low frequency turbulence and in regions of field-aligned current. Individual electric field spikes are well-correlated with small-scale gradients in particle fluxes and small-scale currents.

Sharp et al. (1981) have examined low energy ion streams in the magnetotail boundary layer lobes and plasma sheet. They find that the boundary layer or plasma mantle consist of plasma of solar wind origin but that the streams in the lobe and plasma sheet have ionospheric composition. Finally, we note that Meng (1981) has presented a statistical survey of the energetic particle population of the magnetotail.

### OTHER PLASMA BOUNDARIES

Other plasma boundaries that were the object of intensive investigation in the past received little attention over the last four years. The polar cusp has been studied mainly with low altitude satellites and rockets. Atmospheric Explorer-D low energy electron and ion data have been examined by Reiff et al. (1980) and Burch et al. (1980) to determine the effect of the interplanetary magnetic field on the cusp. When the interplanetary magnetic field is southward the average energy of ions decreases towards the pole. When the interplanetary magnetic field is northward it decreases and then increases. The former signature is interpreted to be consistent with merging and the latter with diffusion. Ion composition measurements from S3-3 show that at times the magnetosheath plasma enters adiabatically while on other occasions the ions appear to have passed through an electrostatic potential in reaching low altitudes (Shelley, 1979). These ion composition data, however, also show that ionospheric ions are continuously being accelerated to energies of the order of keV with the cusp region. Meng (1980) has examined the variation in polar cusp position during a geomagnetic storm. Curtis et al. (1979) have examined high altitude observations of plasma waves in the cusp during substorms. A region almost devoid of plasma has been discovered by Calvert (1981) at high invariant latitudes in the night magnetosphere on the basis of inferred density determined from natural plasma wave observations. This auroral plasma cavity, as it has been called, has densities below  $1 \text{ cm}^{-3}$  at distances of  $2 R_E$  and above and is believed to be a transient phenomenon associated with the generation of AKR.

Another topic that has received very little attention lately is the injection boundary of substorm particles and the nose events of Explorer 45. This appears to be in part because it is now fairly well understood and in part because new and exciting plasma injection mechanisms have been discovered. In the steady-state electric and

magnetic fields of the magnetosphere plasma can drift from the plasma sheet and around outside of some demarcation boundary. Inside this boundary which varies with pitch angle and energy, plasma circulates on closed paths and does not intersect with the plasma sheet. During substorms the convection electric field in the magnetosphere increases and decreases on time scales comparable to the drift time of this plasma. Kaye and Kivelson (1979), Southwood and Kaye (1979), Kivelson et al. (1980) and Ejiri et al. (1980) successfully use simple electric field models and time variations of these models to replicate the observed substorm-associated features of the low energy plasma. The more comprehensive Rice model is discussed by Walker (this issue, 1982).

In the area of understanding ion injection in the magnetosphere attention is now being focussed on field-aligned flows from the ionosphere. When these ion beams peak at some angle intermediate between  $0^\circ$  and  $90^\circ$  pitch angle they are termed conics. Such distributions have been seen deep in the magnetosphere with the ISEE-1 plasma composition experiment in all three primary ionospheric species (Horwitz et al., 1982). Measurements with the ATS-6 plasma spectrometer also reveal field-aligned thermal ions in the midnight region (Olsen, 1982). An even more exotic pitch angle distribution has been discovered with the ion analyzers on the P78-2 satellite (a.k.a. SCATHA) and termed ion 'zipper' (Fennel et al., 1981). These ions are predominantly field-aligned at low energies and predominantly peaked perpendicular to the field at high energies with a very narrow transition in energy. They have been called zipper events because of their appearance on energy-time spectrograms made using a detector that scans in pitch angle. The two components of the zipper are quite distinct in their magnetospheric drift paths. The low energy component drifts to the dayside via local morning and the high energy component by local evening. Ion composition measurements show that the low energy parallel component is mainly composed of oxygen and the high energy perpendicular component

### THE FUTURE

While much has been learned about the outer magnetospheric boundaries from the ISEE-1 and -2 missions, the analysis of data from these spacecraft has far to go. Thus, we should expect many new results still from this mission. The Dynamics Explorer mission has just been launched and we should learn much auroral plasmas at mid and low altitudes in the near future. However, we will not learn much about the distant polar cusp until new spacecraft are launched. Hopefully, the Polar Plasma Laboratory of the OPEN mission which is now being planned will fill this void.

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Figure Captions

Figure 6. Histograms of the velocity and thickness of the magnetopause current layer (Berchem and Russell, 1982a).

Figure 7. Northward moving flux transfer event seen a) from the magnetosheath, b) from the magnetosphere in the boundary layer. Cross sections along paths A-A<sup>1</sup> and B-B<sup>1</sup> shown in panels a) and b) are drawn in panels c) and d).

Figure 8. ISEE plasma and magnetic field data obtained during steady reconnection event on September 8, 1978. From top to bottom are ion number density, velocity, north-south component of magnetic field, plasma (solid) and field (dashed) pressure and total pressure. Abbreviations in the top panel stand for ring current (RC), boundary layer (BL), magnetopause (MP), and magnetosheath (MS).

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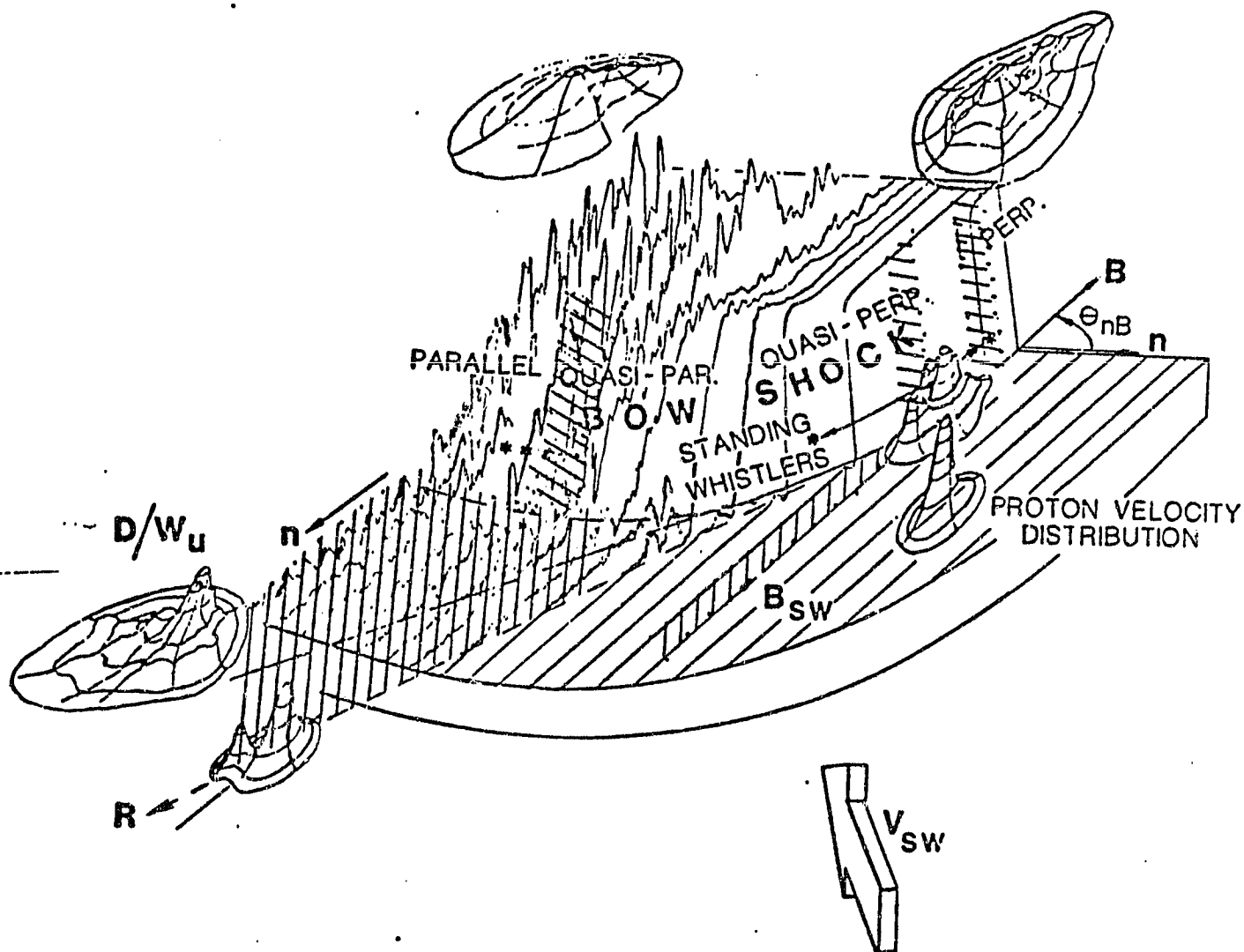


Figure 1. Schematic illustration of nonuniform bow shock structure in average solar wind with magnetic field at average stream angle. Small inserts represent proton spectra at indicated locations;  $R$  refers to reflected ion beams,  $D/W_u$  to diffuse ions and ULF waves. Shading signifies parts of shock system that have been studied.

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LAMINAR	QUASI-PERPENDICULAR
QUASI-LAMINAR	
QUASI-TURBULENT	
TURBULENT	QUASI-PARALLEL

Figure 2. Table of shock designations, with shading to signify areas of study.



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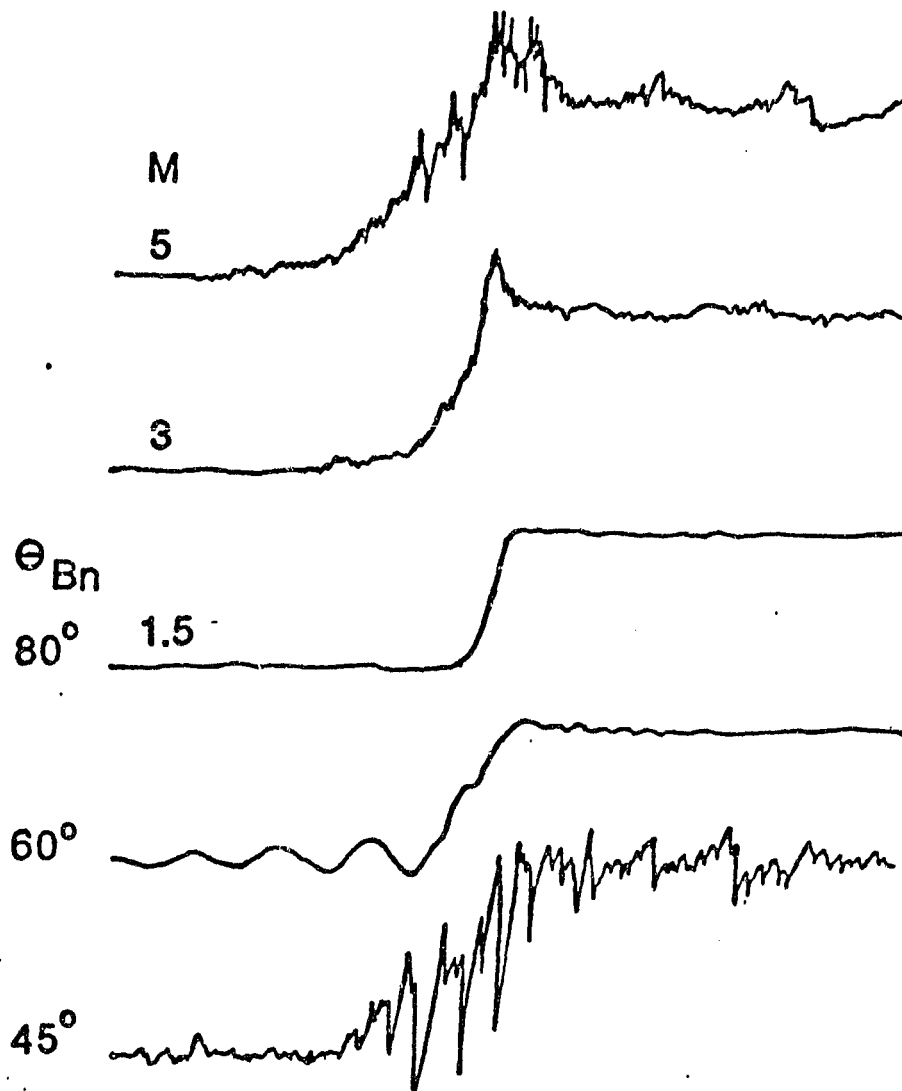


Figure 3. Schematic, Quasi-perpendicular shock profiles for varying Mach numbers and propagation angles.

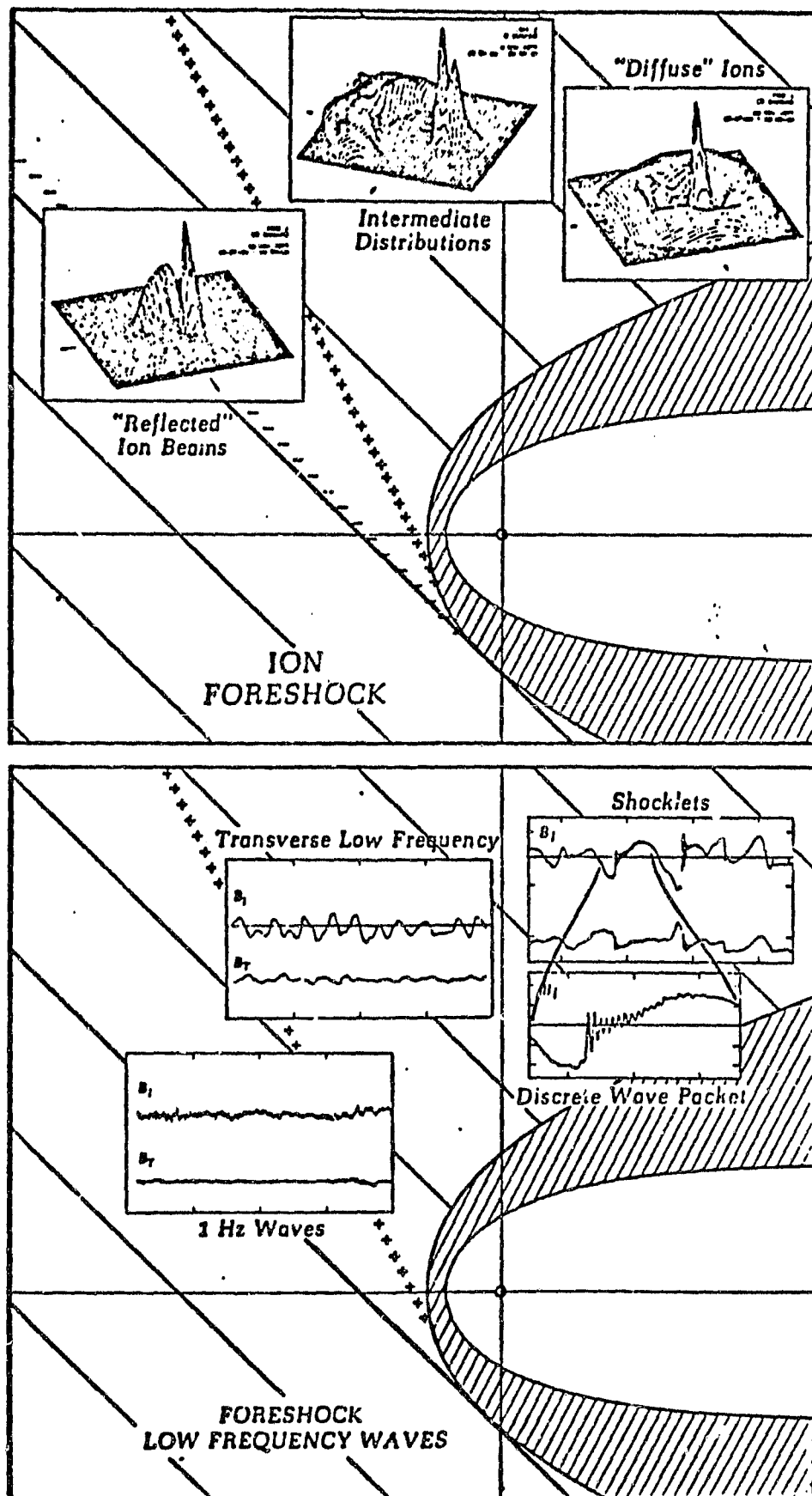


Figure 4. Ecliptic-plane view of corresponding ion distributions and ULF waveforms in the earth's foreshock for stream angle IMF.

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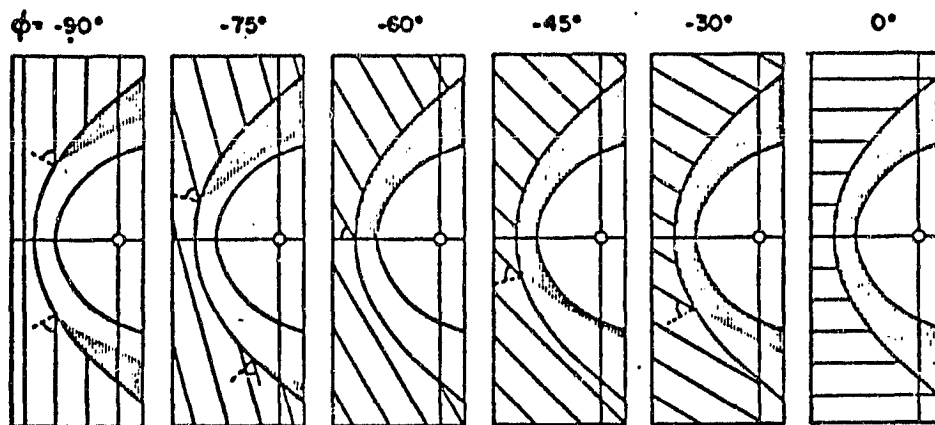


Figure 5. Schematic ecliptic-plane views of the magnetosheath for six different IMF orientations labeled by their azimuth in the ecliptic. Shaded areas are predicted regions of energetic ions bounded by streamlines intersecting the bow shock at points where the angles between the IMF and the dashed normals are  $60^\circ$ .

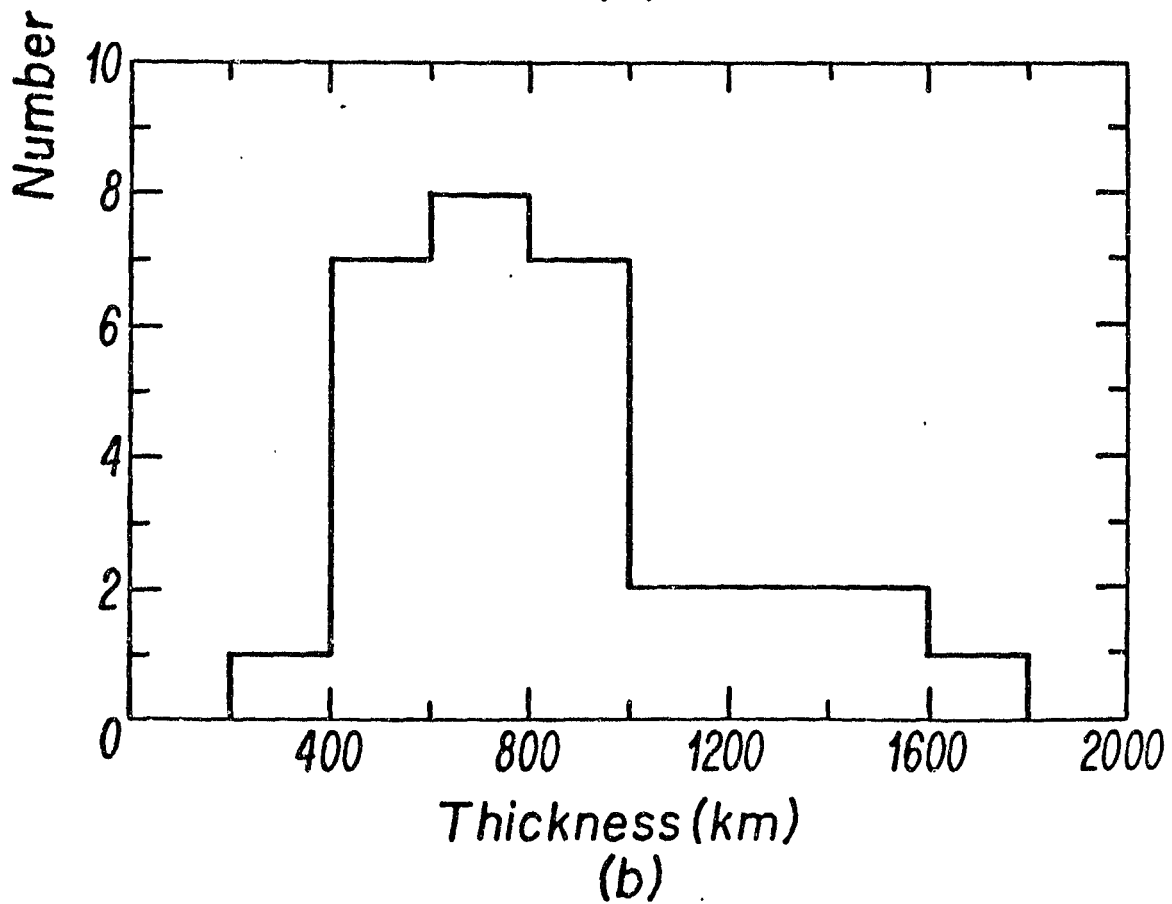
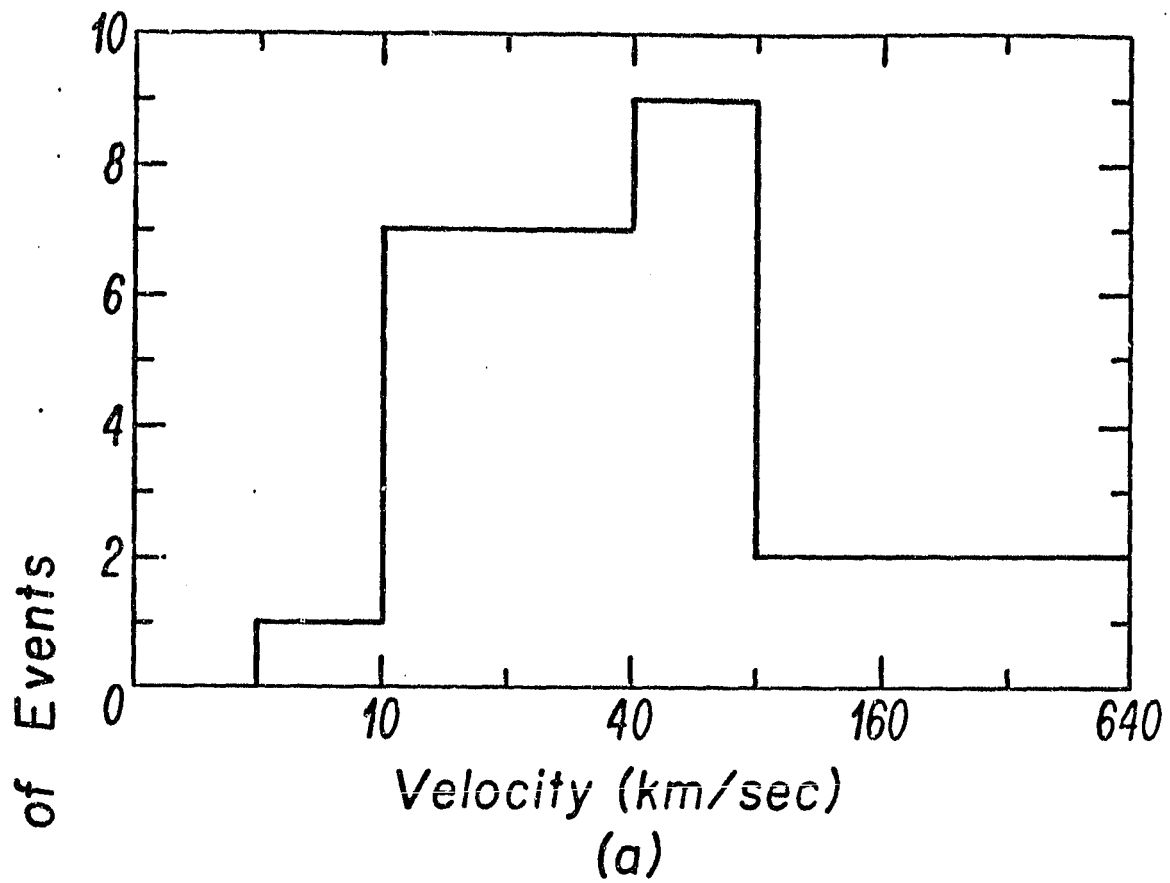
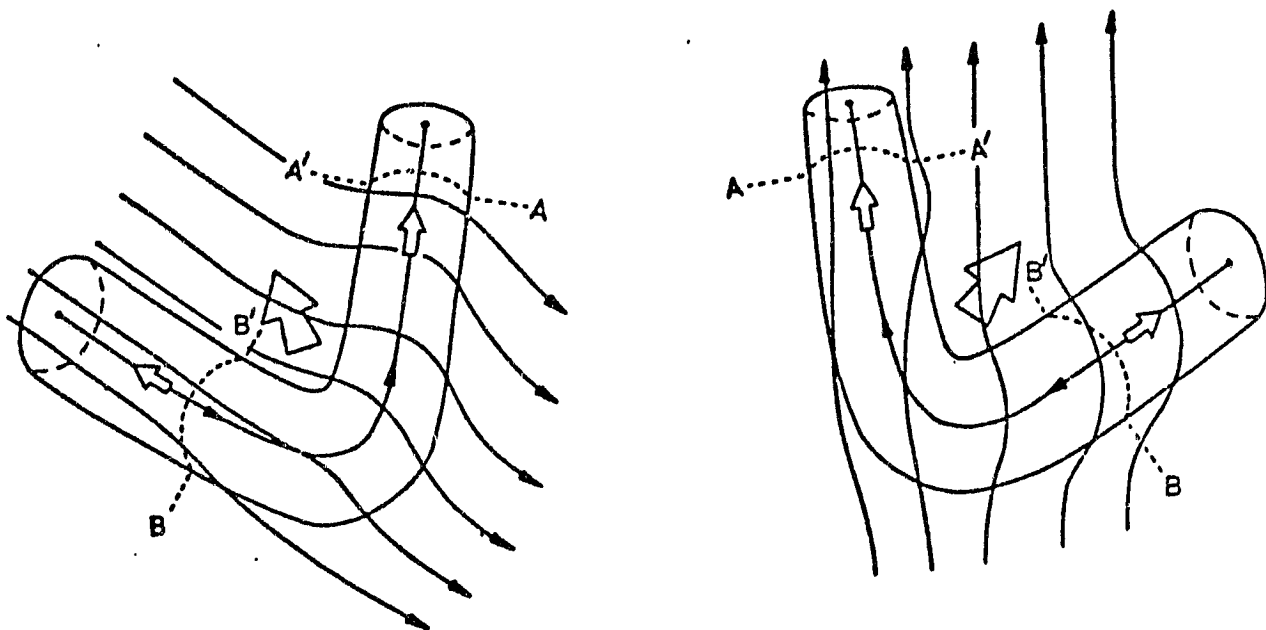


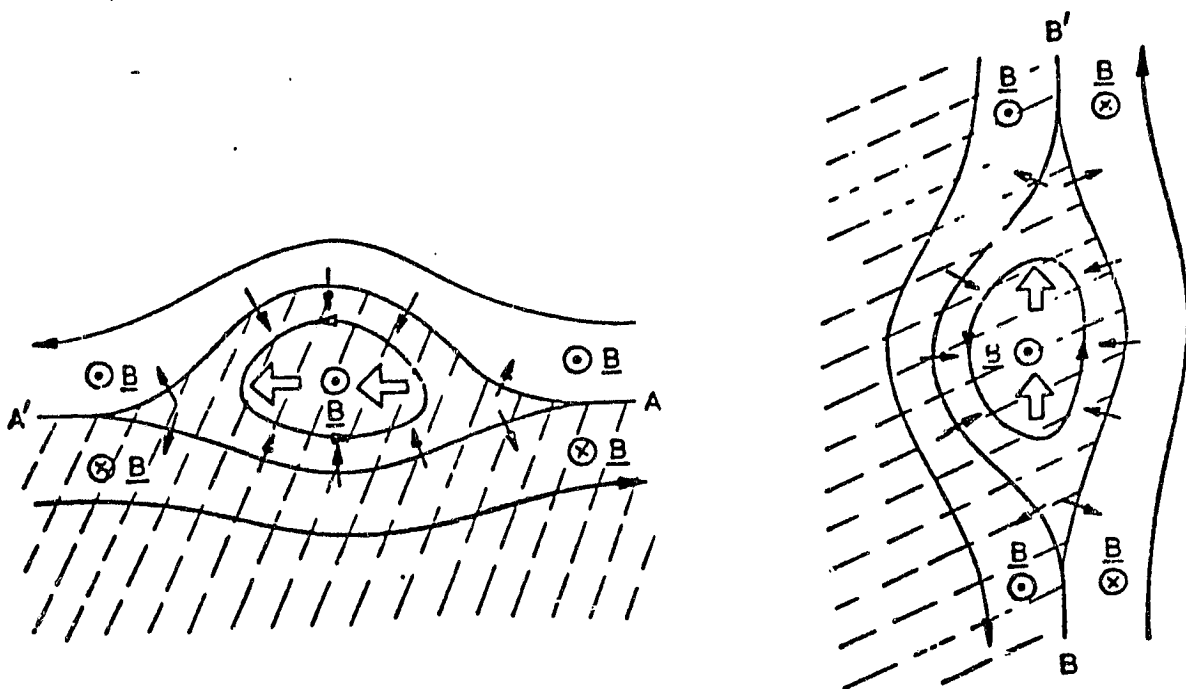
Figure 6

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(a)

(b)



(c)

(d)

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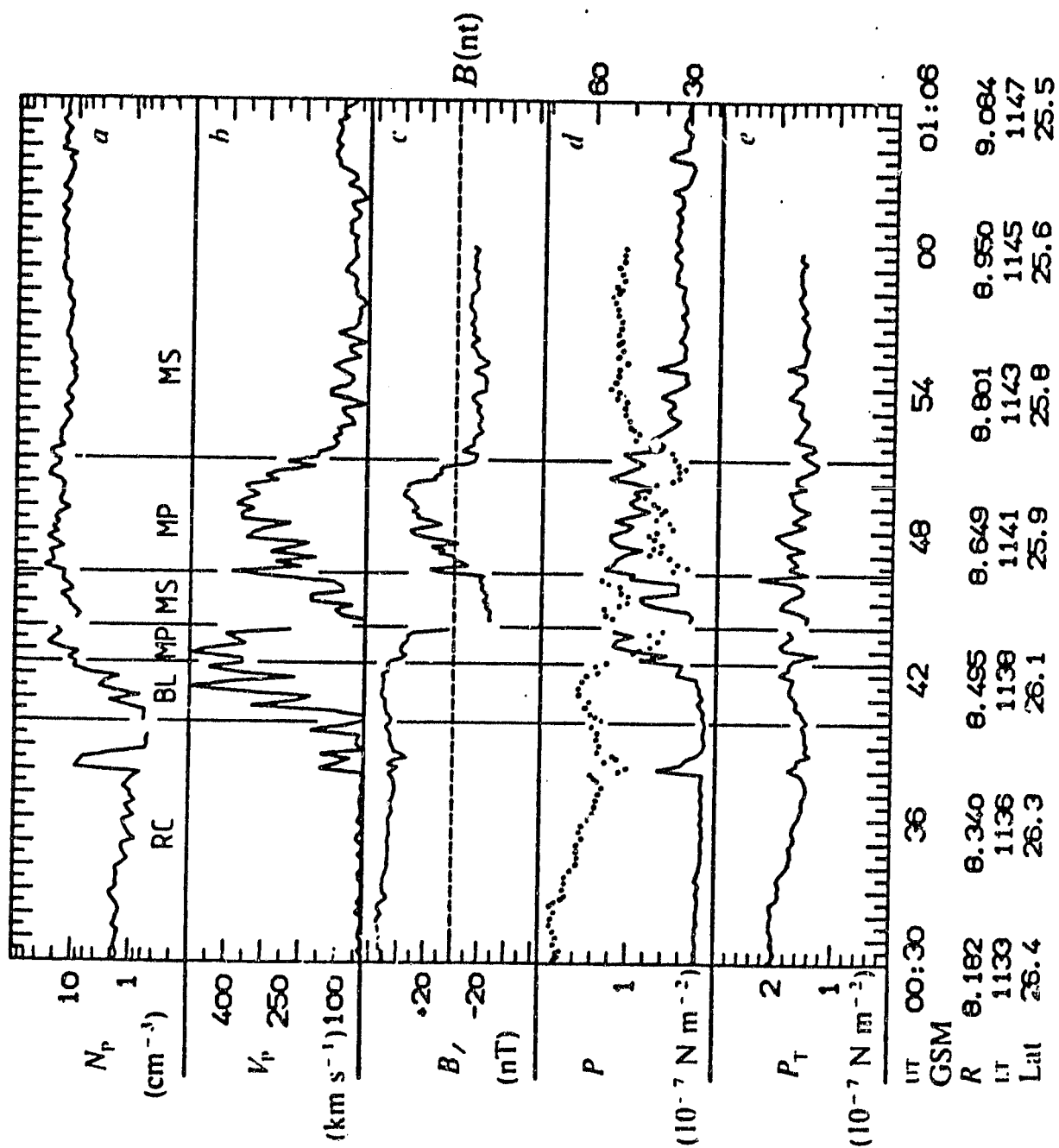


Figure 8